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EOS

Earth & Space Science News

100 YEARS

Time to Take a Hard Look at Geoengineering

How to Keep Rivers Flowing When Dams Are in Demand

What Made the Largest Geoid Anomaly in the World?

THE (NEW) SCIENCE OF APOLLO

AGU 100
ADVANCING EARTH AND SPACE SCIENCE

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Spacecraft 107's Big Trip

Scribbled in ballpoint pen on an equipment bay panel in pilot Michael Collins's handwriting are the words

Spacecraft 107, alias Apollo 11, alias "Columbia." The Best Ship to Come Down the Line.

For all that we celebrate the feat of engineering of the first Moon landing, it hits us hardest when we remember how human it all was.

If it's hard to imagine walking on the Moon, we can easily imagine Collins's immense pride as he rode the USS *Hornet* to Hawaii after splashdown, uncapping his pen to leave behind a mark that commemorated this wild mission. (Technology later revealed that it was twice the pride: Three-dimensional imaging of *Columbia,* Apollo 11's command module, by the Smithsonian Institution in 2016 revealed that Collins had come back to the ship later, likely while he was in quarantine at the Johnson Space Center, and had written over his note again to preserve it.)

AGU has the honor of celebrating the fiftieth anniversary of the first Moon landing along with our own Centennial. Join us at the National Archives in Washington, D.C., later this month, when AGU will be sponsoring a geology panel discussion followed by a screening of the 2019 documentary *Apollo 11*—we'll relive the excitement of that day through footage newly found and digitized by Archives researchers.

We also celebrate the legacy of Apollo in the pages of *Eos*. Our cover story (p. 20) looks at the science that came out of the 382 kilograms of Moon rocks hauled back by the astronauts. As recently as this past January, scientists announced a new discovery from the Apollo 14 mission (p. 4) zircon grains common to Earth but unique to the Moon—which is to say, lunar-roving astronauts may have brought back an Earth meteorite!

NASA researchers had the foresight not to put all these alien treasures under the microscope as soon as they got their hands on them—a portion was held back and protected from our atmosphere so that today's scientists could use modern technology on untouched specimens. We know we're not alone in our excitement at what they might discover about our closest planetary neighbor.

While we reflect on how those space missions changed so much about the way we view our place in the universe, we continue to be inspired by new opportunities for exploration. Telepresence, wherein astronauts in orbit around the Moon or Mars would guide robots on the ground, is shaping up to be the next big thing in space exploration. Meanwhile, experts here on Earth are first guiding this technology underground. On p. 30, read about a team testing robots that can autonomously navigate through flooded mines. The idea is less romantic, perhaps—there's no one to call back that the Eagle has landed—but sending in robots to such treacherously dangerous terrain is likely the best way to keep pushing our boundaries of exploration.

Our forays into space technology have led us to new adventures on Earth as well. Geoid anomaly maps created by satellite observations have revealed strangeness in the Indian Ocean. On p. 26, read about the Indian research team that is on the hunt for the "missing mass" that will explain the largest geoid anomaly in the world. Theories abound: Is the anomaly due to structural undulation in the core-mantle boundary? Seismic low-velocity anomalies in the upper mantle? A "slab graveyard" in the lower mantle? To find out, the team headed to the source and deployed seismic sensors to record data for a year. We eagerly await their results.

Behind all science is the excitement of exploration and the thrill of discovery. In every issue, *Eos* dedicates its final page to such adventurers with Postcards from the Field. This month we hear from a team hand-digging paleoseismic trenches in the Teton Range.

We urge you all to keep exploring, keep discovering—and send us a postcard!

Heather G

Heather Goss, Editor in Chief

Eos

AGU100 ADVANCING EARTH AND SPACE SCIENCE

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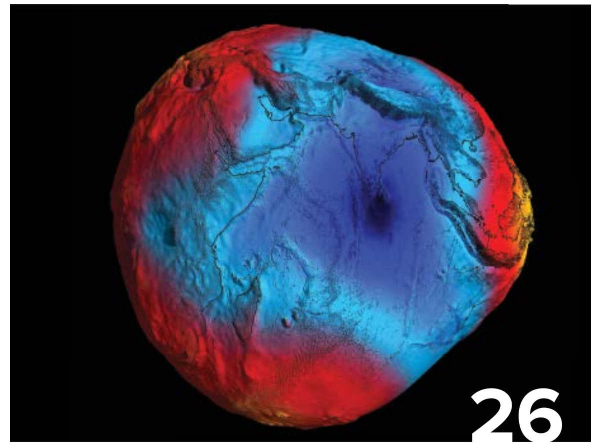

Cover Story

On the Cover

Apollo 11 sample 10019, a brecciated rock.
Credit: NASA/Johnson Space Center/Lunar and Planetary Institute

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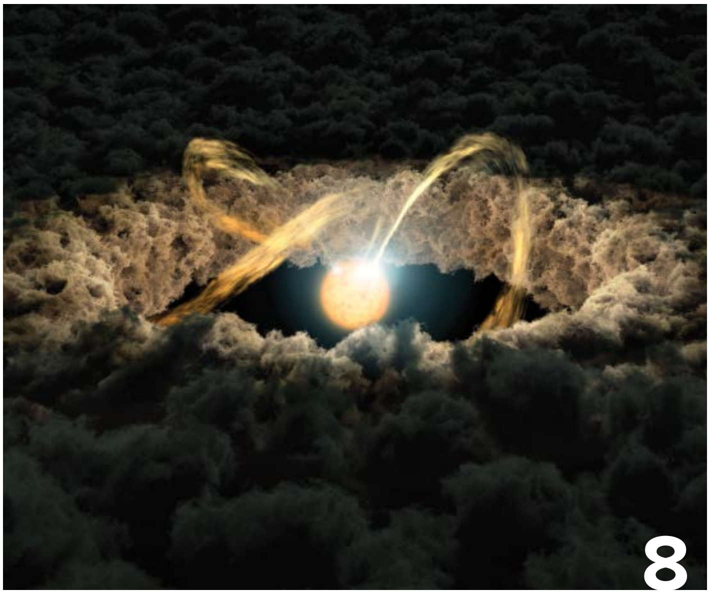

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EOS CENTENNIAL COLLECTION

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Apollo May Have Found an Earth Meteorite on the Moon

A rock sample brought back by Apollo 14 may contain the first evidence of Earth material on the Moon. Recent analysis of zircon grains in one lunar sample suggests that the zircon formed under conditions typical in Earth's crust and not on the Moon.

"We have searched in a lot of Apollo rocks," said Jeremy Bellucci. "In theory, this is the first and only piece of Earth we have found outside of Earth." Bellucci is a geochemist in the Department of Geosciences at the Swedish Museum of Natural History in Stockholm and lead author on a research paper (bit.ly/zircon-apollo) that presented these results in January.

The geochemistry and crystallization environment of the two zircon grains would be "unique to the Moon yet common to Earth," the team wrote in its paper. If the zircons' origin is verified, these grains would be some of the oldest Earth minerals discovered to date and would give a new look into Earth's hellish early years.

The Apollo 14 landing site as seen by the Lunar Reconnaissance Orbiter on 25 January 2011. The descent module landing site is seen as a dark spot northwest of the three craters at bottom left in this image. A faint dark trail from the landing site to nearby Cone crater (top right) marks the path of the astronauts' exploration of Fra Mauro. Credit: NASA/GSFC/Arizona State University

The zircons crystallized in an oxygen-rich and possibly water rich environment that would be unusual for the Moon but common in Earth's crust.

Two Old Zircons

The Apollo 14 astronauts landed on the Moon in 1971 and collected nearly 43 kilograms of lunar material that they brought back to Earth. Scientists have been studying these Moon rocks for decades to learn more about the Moon's minerology, geochemistry, impact history, and magnetic environment.

One sample the astronauts returned with was cataloged as 14321, a 9-kilogram boulder nicknamed "Big Bertha." Cutting into this boulder revealed a clast of granite that contained two zircon grains in a complex breccia. Zircons serve as an important paleoarchive on Earth, recording the time, temperature, pressure, and geochemistry at the time they formed. The oldest zircons, those from Jack Hills, Australia, may be nearly 4.4 billion years old.

Past studies have shown that these two lunar zircons are about 4.1 billion years old and formed during a tumultuous time in the solar system's history called the Late Heavy Bombardment. Scientists think that Big Bertha, along with the other samples collected during Apollo 14, is lunar debris from an impact that formed Mare Imbrium. But Bellucci and his team believe that the two zircons were born even farther away.

A Lot of Weird Things

The researchers analyzed the geochemistry of the zircons and the surrounding breccia to determine their formation environment. They calculated the crystallization pressure by measuring the concentration of titanium in the zircons and in breccia grains with an ion mass spectrometer. On the basis of this measurement, the team found that the crystallization pressure translated to a depth of about 170 kilometers below the Moon's surface.

Bellucci and his team then simulated how deeply the Imbrium impact would have excavated the Moon's surface. Their models suggest that material from the base of the lunar crust, about 30–70 kilometers deep, was ejected from the crater. This depth is far shallower than that where the zircons would have crystallized had they formed on the Moon, the team noted.

On Earth, however, the crystallization pressure corresponds to about 20 kilometers deep in Earth's crust, a region that easily might have been excavated by an impact, Bellucci said.

Next, the team measured the concentration of oxidized cerium ions in the two zircon grains. This measurement was used as a proxy for the amount of freely available oxygen at the time the zircons crystallized. The cerium measurements showed that the zircons crystallized in an oxygen-rich and possibly water rich environment that would be unusual for the Moon but common in Earth's crust.

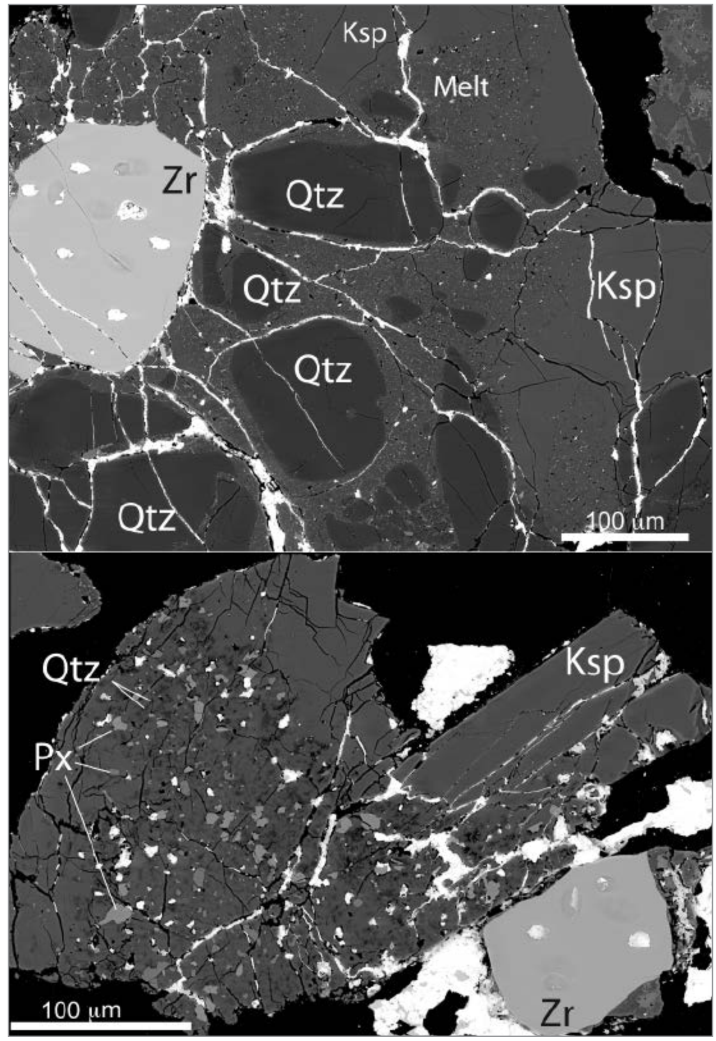
The cerium measurements also revealed that the zircons crystallized at a temperature much lower than for other lunar magmas and is more in line with shallow-crust minerals on Earth.

"A lot of weird things happened in this clast where these zircons came from" if they came from the Moon, Bellucci said. The breccia that surrounds the zircons, however, has Moon-like geochemistry.

The Moon or Earth?

Nevertheless, the researchers considered whether the sample could have formed

Apollo 14 sample 14321, nicknamed "Big Bertha." Credit: NASA/Johnson Space Center photograph S71-29184



Backscatter electron images of two zircons (Zr) from Apollo sample 14321. The zircons are surrounded by potassium feldspar (Ksp), iron-infused melt glass (melt), pyroxene (Px), and quartz (Qtz). Credit: Bellucci et al., 2019, https://doi.org/10.1016/j.epsl.2019.01.010, Figure 1

entirely on the Moon near Mare Imbrium. The Imbrium impact then would have ejected the clast to its eventual home at the Apollo 14 landing site. In this scenario, a shock wave associated with the impact would provide the higher crystallization pressure. However, the shock wave also would have left behind other signs in the grains that are notably absent, the team said.

But if the zircons formed in Earth's crust during the Hadean (>4.0 billion years ago), that would explain the low-temperature, high-pressure, and high-oxidation environment in which the zircons crystallized, Bellucci's team argues. An impact on Earth might have ejected the material to the Moon, some of which then mixed with lunar material. This mixing would explain why some of the sample's grains suggest a lunar origin while the zircons suggest a terrestrial one, Bellucci explained.

"We have no rocks on Earth that are older than about 4 billion years," Bellucci said. "Most of the material from before 4 billion years ago are the zircons from Jack Hills. If the Moon has pieces of Earth that arrived there during the Late Heavy Bombardment, they must have formed before 3.9 billion years ago."

"[The Moon] could serve as an inventory to study the Hadean Earth, which we don't have any pieces of anymore on Earth," he added.

First of Its Kind

The results are "very intriguing," according to Carolyn Crow, a research associate in geological sciences at the University of Colorado Boulder who was not involved with this research. "These zircons do appear to have more Earth-like trace element compositions relative to the rest of the Apollo zircons," she told *Eos*.

However, Crow cautioned that some of the team's assumptions—particularly that the zircon, quartz, and other minerals in the breccia crystallized at the same time—still need to be verified. If the assumption is false, that could rule out Earth as an origin. "That being said," she continued, "if further work is able to confirm that this assumption holds true, then this would be compelling evidence for a terrestrial meteorite on the Moon."

"I expect there could be a bit of controversy because this is the first of its kind," Bellucci said. "Hopefully, it inspires a search for more Earth materials and further analyses on these samples."

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

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Climate Geoengineering Study Will Examine Risks and Benefits

With growing concerns about the impacts of climate change, a new study is examining whether controversial geoengineering approaches to try to cool Earth should be considered along with mitigation, adaptation to unavoidable climate change impacts, and other measures.

A committee of the U.S. National Academies of Sciences, Engineering, and Medicine (NASEM) has started developing a research agenda and exploring approaches for climate intervention (CI) strategies to cool Earth.

The committee, which held its first meeting on 30 April, is looking into sunlight reflection strategies that involve atmospheric interventions, according to the committee's statement of task. These strategies include marine cloud brightening, stratospheric aerosol injection, and cirrus cloud modification.

The committee will examine the positive and negative impacts and risks of these interventions on the atmosphere, climate systems, natural and managed ecosystems, and human systems, and explore what research and infrastructures are needed, according to the statement.

Though these interventions could reduce some risks of climate change, they also introduce potential environmental, ethical, social, political, economic, and legal risks—and concerns about these risks have constrained research on the topic.

A committee of the U.S. National Academies of Sciences, Engineering, and Medicine has started working on developing a research agenda for climate intervention strategies that reflect sunlight to cool Earth. Credit: iStock.com/modestbike

How Do You Balance the Risks?

How to balance the risks from climate change against the potential risks from possible solar climate interventions "is a really hard question," committee cochair Christopher Field told *Eos.*

"That's part of the reason that we would want to understand much more about the potential of the interventions and their risks before even having any kind of serious discussion about whether they should be included in a portfolio of responses" to climate change, said Field, a climate scientist who is director of the Stanford Woods Institute for the Environment at Stanford University in California. "We are just way too early in the development of the dialogue to have a mature response to that."

The committee also plans to look into governance mechanisms that could encourage public participation and consultation in research planning and oversight and that could ensure transparency and accountability about a project, including a project's potential risks.

The Right Timing for a Study

"We think the timing is right for a comprehensive study, such as the one that the National Academy of Science (NAS) completed in 2015, given the increasing interest in this issue and large remaining uncertainties in both the scientific and governance arenas," according to a statement by the National Oceanic and Atmospheric Administration (NOAA), one of the study's sponsors. David Fahey, director of the Chemical Sciences Division of NOAA's Earth System Research Laboratory in Boulder, Colo., presented the statement at the meeting.

> "Solar geoengineering is the worst possible way to address climate change that we need to take seriously."

However, the statement continued, "our support for this study should not be interpreted as reflecting support for future implementation of [climate intervention] methods to reflect sunlight."

Fahey noted that the committee's work could help to guide NOAA's efforts. "There is no federal program for geoengineering," although there is a lot of research relevant to geoengineering, he said. "The elephant in the room here is urgency," Fahey continued. "Urgency tends to override all of these nicer considerations about 'should we do it' and 'what about the balance of risks.'"

Taking a Hard Look at All Possible Approaches

"There are real risks that we may not get there in terms of limiting dangerous climate change only through the technologies that many of us prefer," committee member Peter Frumhoff told *Eos.* "From my perspective, solar geoengineering is the worst possible way to address climate change that we need to take seriously." Frumhoff is director of

science and policy and chief climate scientist at the nonprofit Union of Concerned Scientists.

"We are no longer at the point in time when, from my perspective, we can avoid taking a hard look at all possible approaches, even those we don't love, and we may ultimately reject them," he said.

Frumhoff added that discussion about climate interventions should not be driven by scientists but should involve a variety of stakeholders, including the most climate-vulnerable nations and communities.

Stakeholder Perspectives

"We view the sunlight reflection techniques as currently among the most high probability options for short-acting solutions to disruptive change. They may be very important in that regard from the point of view of protecting people, ecosystems, and economic systems" from the threat of climate change, said Kelly Wanser, executive director of SilverLining, a Washington, D.C.–based nonprofit whose mission is to drive research to improve the ability to forecast climate and understand the risks and feasibility of interventions to reduce warming.

> "We can't afford to take anything off the table."

Janos Pasztor, executive director of the Carnegie Climate Geoengineering Governance Initiative of the Carnegie Council for Ethics in International Affairs, emphasized that research on solar radiation management "should not be considered to be an alternative to research on, and implementation of, emission reductions and renewables."

"The committee should recognize and acknowledge the strong and very widespread opposition to these forms of geoengineering within civil society and social movements across the world," said Lili Fuhr, another speaker at the meeting. Fuhr is head of the Ecology and Sustainable Development Department of the Heinrich Böll Foundation, a nonprofit affiliated with, but independent of, the German Green Party.

What We Don't Know

Andrew Light, a professor of philosophy, public policy, and atmospheric sciences at George Mason University and a senior fellow in the climate program at the nonprofit World Resources Institute, told *Eos* that he doesn't know anybody in the research community who seriously imagines that climate interventions would be a substitute for climate mitigation.

"But the fact of the matter is that we know enough now about how quickly the climate is changing and how bad the impacts are going to be if we don't meet some of the internationally agreed upon targets that we have right now, that we have to consider whether this [climate intervention] is possible," Light said. "I would like to know what we don't know about these kinds of proposals, which have been around for decades. We can't afford to take anything off the table," he added.

By **Randy Showstack** (@RandyShowstack), Staff Writer

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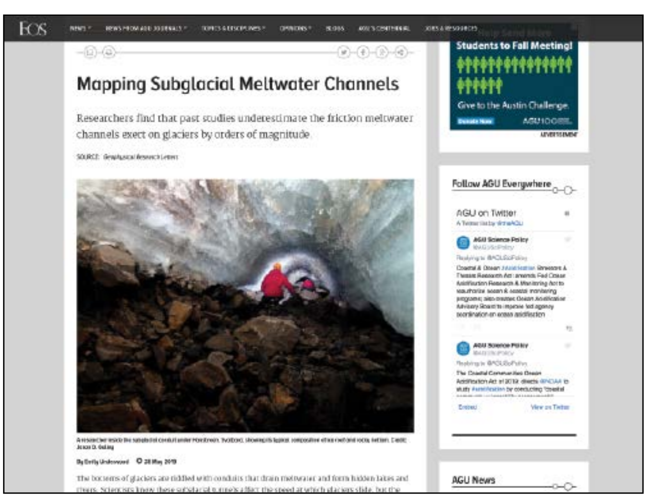

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Passing Object May Have Kicked Up Dust from a Planetary Disk

A protoplanetary disk in a rare configuration is providing insights into how passing objects may influence the way planets form.

Surrounding the star SU Aurigae, the protoplanetary disk features an extended tail of gas and dust. New research suggests that the tail most likely formed as a result of a flyby from a substellar object, which dragged out some of the gas and dust from the disk. Interactions between disks and passing objects may help to explain the wide variety of planetary systems spotted around other stars, according to research recently published in the *Astronomical Journal* (bit.ly/protoplanetary-disk-tail).

Stars form when a cloud of gas and dust collapses in on itself. After a star is born, leftover material can spin into a disk that can go on to build planets. Passing stars, clouds of gas, and even giant planets can gravitationally collide with the young disk, shaking up how young planets evolve.

"If the collision occurs during planet formation, the orbits of [the young] planets are scattered drastically," says Eiji Akiyama, an astronomer at Japan's Hokkaido University and the lead author of the new research. "Some of them could be pushed out from the planetary system and exist as free-floating planets."

Tracking Down the Tail

Akiyama and his colleagues had previously studied SU Aurigae with the Subaru Telescope on top of Hawaii's Mauna Kea. They found that the young disk had a small tail of dust that extends approximately 350 astronomical units (AU), where 1 AU is the distance between Earth and the Sun. The discovery piqued their interest, and they decided to probe the disk again with the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile to better understand the unusual feature. ALMA revealed an even longer, gas-filled tail that stretched more than 1,000 AU.

The most likely candidate for creating the tail is a passing substellar object, according to the authors. As a brown dwarf or giant planet zipped by the newborn star, material in the outskirts of the disk would have felt a stronger gravitational pull from the interloper than from its sun. According to Akiyama, the substellar object would have made its pass only a few hundred years ago, an eyeblink in astronomical timescales.

Although it's possible that the tail could have been formed by a planet ejected from the disk itself, the authors think that scenario is unlikely because the motion of the tail appears to argue against it. Objects from inside the disk would continue to rotate around the star, creating a curved tail that would wrap around it. Instead, the tail stretches away from the star.

The tail is "almost running away from [the star]," says Joseph Rodriguez, an astronomer at the Harvard-Smithsonian Center for Astrophysics not involved in the research. Like breadcrumbs, the escaping tail could indicate the direction the intruder traveled.

The young disk had a small tail of dust that extends approximately 350 astronomical units.

Rodriguez studied RW Aurigae, whose tail was most likely created by a companion star. So far, SU Aurigae and RW Aurigae are the only protoplanetary disks known to have an extended stream of material. The question Rodriguez and his colleagues are pondering is whether that's because such interactions are rare or because they just haven't been spotted yet.

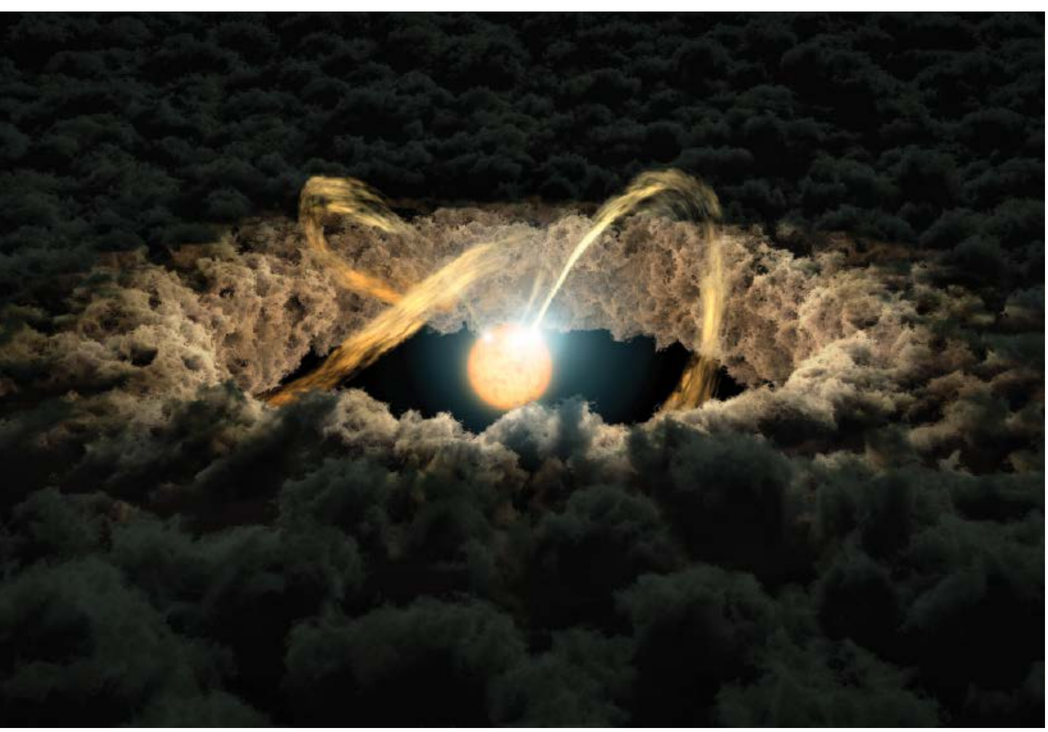
Anna Miotello, a postdoctoral fellow at the European Southern Observatory in Germany who was not part of the research, suspects that the limits of technology play a significant role in the lack of evidence of such disks. Although protoplanetary disks have been observed for decades, ALMA has provided more detailed observations of only a handful of objects.

"I think it's quite exciting to see this kind of data," Miotello says.

Both Rodriguez and Miotello agree that more such disks need to be observed to better understand how they affect the way planets form. In the meantime, Akiyama and his team are turning their eyes back toward SU Aurigae to take a more in-depth look at the tail with ALMA.

"We will try to find the origin of the tail-like structure," Akiyama says. "It will tell us how such a structure impacts planetary formation."

By **Nola Taylor Redd,** Science Journalist



A passing substellar object, such as a giant planet or brown dwarf, may have invaded the cloudy protoplanetary disk of SU Aurigae, creating a trail of gas and dust behind it. Credit: NASA/JPL-Caltech

The Blob Causing Earthquakes

A team of Afghan and U.S. scientists installs a continuous GPS instrument above Fayzabad, Afghanistan. The data gleaned from this fieldwork helped reveal the presence of the blob beneath the Hindu Kush. Credit: Dylan Schmeelk

The next time you shut off the water at the sink, stick around for a minute and peer at the faucet spout. You might see a droplet of water form there and then pull away until, at last, it breaks free and falls through the air.

This same process, more or less, is happening to Earth's continental lithosphere beneath a region of the Eurasian tectonic plate known as the Hindu Kush mountains, which straddle Afghanistan and Pakistan. There, a pair of geophysicists found a "drip," or a "blob" of continent, that is, like our water droplet, pulling away from the lithosphere and descending into the mantle.

The blob, the team reported in April in the AGU journal *Tectonics* (bit.ly/blob-earthquake), looks like a droplet that is just about ready to break off of its spout. The mass is pulling away from the crust at a rate as fast as about 100 millimeters per year, and as it moves, it triggers earthquakes that scientists have been unable to explain the origin of—until now.

"We never quite understood the Hindu Kush earthquakes," said geophysicist Peter Molnar of the University of Colorado Boulder, who led the research.

That's because these earthquakes defy convention: They do not happen along an obvious path, or lineament, as is often the case in seismic zones elsewhere on the planet. Instead, the pattern of the Hindu Kush earthquakes resembles something akin to a "round patch" on the planet's surface, said Rebecca Bendick, a geophysicist at the University of Montana in Missoula who coauthored the new research alongside Molnar.

One part of the mystery relates to the fact that there is no obvious tectonic feature in that part of the world that researchers might point to as a driver behind the region's quakes. Nevertheless, "there's a long catalog of earthquakes happening underneath the Hindu Kush to very unusual depths," Bendick said.

To unravel what might be going on, Molnar and Bendick, employing a team of Afghan scientists, gathered seismic data around the Hindu Kush area over the past several years. A picture of a dripping blob began to emerge on the basis of where quakes happened at different depths. Although the team does not know for sure just how big the blob is, the seismic data suggest that it spans a 300-kilometer-deep zone that is about 150 kilometers north to south and about 100 kilometers east to west—not quite as large as the continent-scale deep-Earth blobs that *Eos* reported on in February (bit.ly/Eos_Earth-blobs).

Geoscientists thought before that the only way that rocks of Earth's lithosphere could cycle into the planet's interior was via subduction, whereby oceanic lithosphere dives beneath continents at tectonic plate boundaries. But now that there is what Bendick sees as definitive proof that dripping blobs of continental lithosphere exist, the subduction-only paradigm may be infirm.

Before, it was thought that continental crust never was really lost over time, and researchers rely on this assumption whenever they rewind the clock and try to figure out where ancient continents were and how they fit together in Earth's deep history. But if the continents can lose parts of themselves over time, those reconstructions may not be entirely accurate.

The Hindu Kush blob, Molnar explained, likely began dripping, at the earliest, only about 10 million years ago. "It's a relatively recent process, and you're stretching out this material so fast that pretty soon it's all gonna drip off and go away," he said.

The dripping is happening relatively quickly, but, Bendick explained, there is no great understanding of how common such blobs are over geologic time. So for now, how much mass continents might be losing, over what timescale, and, in turn, how inaccurate reconstructions of ancient continents may be will remain unknown.

Nevertheless, one mystery that researchers can consider solved is the fact that blobs do indeed exist, explained Philip England, a geophysicist at the University of Oxford in the United Kingdom who was not involved in the work.

"Molnar and Bendick's elegant analysis identifies one such drip," England said. The find, he added, should help with identifying and studying blobs that exist elsewhere within the planet.

By **Lucas Joel,** Freelance Journalist

Where Did All the Free-Flowing Rivers Go?

The Mekong River weaves between mountain walls in Luang Prabang, Laos. Credit: iStock.com/holgs

Giant catfish once swam in the golden-brown waters of the Mekong River near the Thai village of Sob Ruak. But since the Chinese government built hydropower dams upstream, the waters now drop too low for the catfish to lay their eggs. The loss of habitat for the catfish is just one of many stressors the increasingly developed river faces.

A new study released 8 May in the journal *Nature* suggests that the Mekong's plight is not unique: Humans have had a significant impact on the majority of the world's 242 longest rivers (see bit.ly/free-river). Just one third of long rivers still flow freely throughout their entire length, and the most untouched rivers exist far from population hubs in the Arctic, the Amazon River Basin, and the Congo River Basin.

The study includes detailed worldwide river maps that give planners a bird's-eye view of human changes across the landscape. As countries race to meet aggressive clean energy goals, the study's authors hope that the maps can inform future hydropower dam projects.

"This study is not meant to be a study that says, 'stop any kind of development,'" Bernhard Lehner, an associate professor in the Department of Geography at McGill University in Montreal, Que., and one of the first authors on the study, told *Eos*. "But it's meant to find smart solutions."

Free to Roam

In the past, scientists relied on hydrologic assessments limited in scope. They used either global data sets of rivers that suffered from low resolution or regional maps that failed to take the whole watershed into consideration. The latest assessment is novel in both its reach and detail.

The team parsed 12 million kilometers of rivers and rated the rivers' degrees of freedom. A free-flowing river can move side to side and ebb and flow naturally, as well as have the ability to replenish groundwater and carry sediment. A free river should also start at its source and flow unimpeded to its end. Together, the scientists call the criteria "four-dimensional" connectivity.

The researchers rated their 12-million-kilometer database in 4-kilometer-long sections. They docked a section's free-flowing status not only for infrastructure like dams and reservoirs but also for projects less easily seen, like sediment traps and irrigation. They even mapped canals using satellite images of night light. The study limited its assessment to rivers longer than 500 kilometers because smaller dams and modifications often go unreported.

The analysis revealed not only that most of the world's longest rivers are no longer free-flowing but also that dams are the overwhelming cause.

"We always come back to dams as being the main culprit in all this," Lehner said.

Dams stop species from migrating upstream, and they also trap sediment, preventing it from flowing down the river. For the Mekong River, more dams will mean less and less sediment transport to the fertile Mekong River delta in southern Vietnam, a hub of the country's agriculture. The Mekong rates below the threshold for a healthy, free-flowing river in the study's assessment.

Murky Waters

Although dams fragment a river and cause a litany of downstream damages, they also provide a source of renewable energy. There are increasingly urgent calls worldwide for lowering greenhouse gas emissions, and hydropower dams are one answer.

Climate change driven by greenhouse gas emissions harms rivers as well: Hotter air temperatures warm river waters and decrease the amount of dissolved oxygen they can hold. Restricting the free flow of rivers by installing hydropower dams will hurt the ecosystem further, according to the new study.

"While we try to counter climate change, it makes the situation in rivers worse for ecology," Lehner noted. "This is the conundrum in this whole story."

> "This study is not meant to be a study that says 'stop any kind of development.' But it's meant to find smart solutions."

Lehner hopes that the new data set, which is available with its source code for free, will give planners a resource to scrutinize the full effects of river management infrastructure.

"We can run thousands of scenarios where we place dams in different locations and see what that would do to [river] connectivity," Lehner noted. If a dam must be built, he reasoned, planners can leverage the tool to put it in the least significant place possible for river connectivity.

Faisal Hossain, a professor of civil and environmental engineering at the University of Washington not involved in the study, told *Eos* that the new research gives engineers like him "an actionable map."

"Such a global map of four-dimensional connectivity allows our community to devise solutions for river infrastructure that are more ecofriendly, greener, and yet can address livelihood needs," he noted. "This is a very brilliant breakdown for the engineering and policy world."

The study's maps can be explored in this interactive map portal: bit.ly/free-river-map.

By **Jenessa Duncombe** (@jrdscience), News Writing and Production Fellow

Airborne Gravity Surveys Are Remaking the U.S. Elevation Map

A GPS station at work surveying southern Colorado. Credit: National Geodetic Survey

For the past 12 years, scientists at the National Geodetic Survey have been on a mission.

The agency has sent planes to fly over thousands of kilometers of the United States in methodical, gridlike patterns in an effort to recalculate elevations across the entire country. The reference system is based on tiny variations in gravity that will define elevation above sea level at any given point. When completed, it will map elevation down to 2 centimeters in some places.

"Worldwide, this has never been done before with this level of accuracy," said William Stone, a geodetic adviser at the National Geodetic Survey (NGS).

In the past, land surveyors building dams, assessing flood risk, laying roads, and developing other infrastructure used a patchwork reference system from the 1980s that relied in large part on static benchmarks scattered around the country. The new reference system, to be released in 2022, will allow surveyors to simply use a global navigation satellite system (GNSS) receiver and the agency's models to determine elevations. The model will include a time-varying component to take into account land subsidence and uplift.

The upgrade to the nation's system of elevations will not only save land surveyors valuable time but also could bolster emerging technologies that depend on detailed spatial information, like self-driving cars and drones.

Stone and others from the agency met with members of the public to discuss the rollout of the new system at the 2019 Geospatial Summit in Silver Spring, Md., in May.

Gravity as a Guide

The United States isn't the first country to conduct airborne gravity surveys in an effort to upgrade elevation reference systems. New Zealand completed its own survey in 2017, and Japan is considering doing the same. But the U.S. project is by far the largest in size, including the whole country and its territories.

Although we can't feel the slight changes in gravity in our everyday lives, the acceleration of gravity fluctuates across Earth's surface depending on the amount of mass present. Near a mountain, the pull of gravity is

stronger because of the mountain's mass, whereas near a valley, the gravitational pull weakens. The change is slight: The pull of gravity might change by a fraction of a percent.

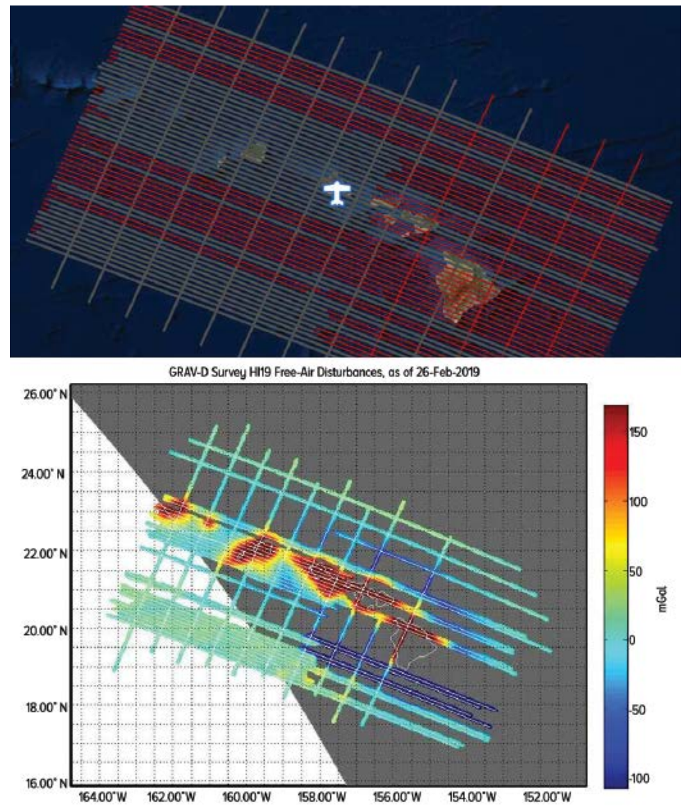
The airborne surveys detect the tiny oscillations in gravity using gravimeters, instruments housed in a series of gimbals and joints to protect them from the plane's vibrations. The gravimeters contain a weighted rod attached to a spring, which flexes over areas with a stronger pull and relaxes over regions with lower gravity. The airborne survey passed its 75% completed mark in February, and the current operation stretches from South Carolina to Hawaii and American Samoa.

A Modern Geoid

The new elevation system will be based on gravity measured across three spatial scales: NASA's Gravity Recovery and Climate Experiment (GRACE) and the European Space Agency's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) satellites, which record gravity changes from space; the airborne survey; and ground-based stations. Together, the measurements combine to create a picture of the gravity contours, which can be used to trace the position of sea level inward.

"It's only recently that we've been able to get a good enough measurement of the gravity field to even consider doing this," Vicki Childers, chief of the Observation and Analysis Division at NGS, said. "It's been kind of the holy grail for a long time."

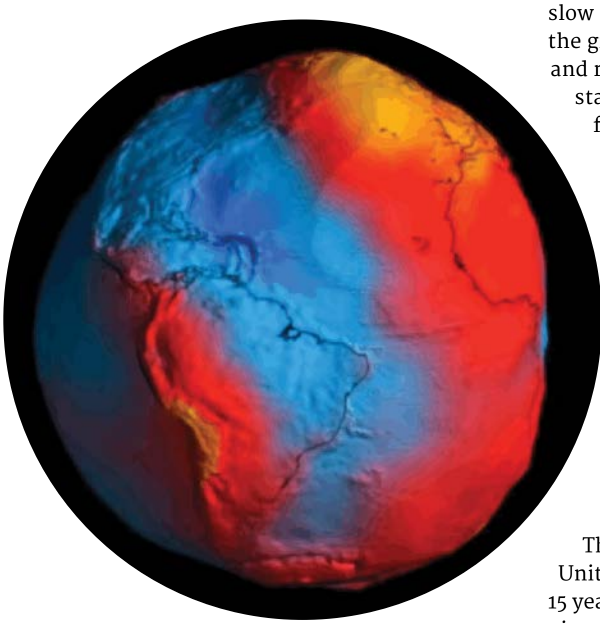
The ultimate goal of the project is to create the equipotential geoid, a map of one particular gravity surface stretching from coast to coast. The geoid allows users to simply determine exact elevation from the coordinates of their GNSS devices. Having the geoid as a resource would cut the amount of time cartographers currently spend surveying by 10, according to a 2007 NGS report.



A plane measures gravity over the Hawaiian island chain in February 2019 for the NGS airborne gravity survey (top). A partially completed gravity survey map (bottom); mGal = milligal. Credit: National Ocean Service/NOAA.

The geoid model will include a novel feature that takes into account the slow movement of the ground sinking and rising over time. Earth's surface is constantly shifting, and the geoid model will factor in those changes. It also offers the model flexibility to include instantaneous changes, like a volcanic eruption or an earthquake.

"Right now, even though we live on a dynamic Earth, our reference system has been stationary," said NGS scientist Kevin Ahlgren. But with the new model, "when that big earthquake happens, we're ready to remeasure things afterward and build that into the model."



Geoid model showing areas of stronger gravity (red) and weaker gravity (blue) measured by the GOCE satellite. Satellite measurements are one of three main sources of gravity information for the National Geodetic Survey's new elevations. Credit: ESA/HPF/DLR

Elevations Redefined

The new elevation data will save the United States an estimated $4.8 billion over 15 years from advances in floodplain mapping, emergency planning, storm surge calculations that affect coastal management, and other activities. The gravity survey, called Gravity for the Redefinition of the American Vertical Datum, is budgeted at just under $40 million.

Updated elevation data are only one part of the massive undertaking by the National Geodetic Survey to redefine the 3-D reference system in the United States, the National Spatial Reference System, that will go live in 2022. The new system includes not only recalculated elevations but updated latitude and longitude data as well (http://bit.ly/spatial-ref).

Taken together, the new abundance of spatial data could augment automated transportation in the future.

"We're right on the precipice of self-driving vehicles," Stone said. Self-driving cars and drones of the future will need extremely accurate 3-D information, according to Stone, as well as a shared reference frame among them. He believes the new NGS reference system could serve as their guide.

"It's going to revolutionize a lot of applications that aren't possible today," Stone said.

By **Jenessa Duncombe** (@jrdscience), News Writing and Production Fellow

A Wildlife Corridors System to Protect Species

Pronghorn antelope, which migrate more than 250 kilometers from winter to summer feeding grounds in the West, would be among many species to benefit from protected wildlife corridors. Credit: iStock.com/Dean_Fikar

Legislation to establish a national system of wildlife corridors in the United States was introduced just days after a United Nations (UN) report was issued in May warning that about 1 million species worldwide are threatened with extinction.

The Wildlife Corridors Conservation Act of 2019 would establish a system to help native animal and plant species—including protected species—that face habitat loss, degradation, fragmentation, or obstructions to connectivity between their habitat areas. The bill aims "to provide long-term habitat connectivity for native species migration, dispersal, adaptation to climate and other environmental change, and genetic exchange."

In addition, the bill would establish a grant program on nonfederal land and water to increase wildlands connectivity. It would also include a stewardship fund to help manage and protect the corridors.

Crucial to Human Existence

The legislation is "a critical step to protect wildlife," Sen. Tom Udall (D-N.M.), who introduced the legislation in the Senate, said at a 16 May briefing about the bill.

"While we are in the middle of a human-caused sixth mass extinction, scientists are raising the alarm. We are almost out of time to save the planet as we know it," Udall commented, referring to the UN report.

The report, which was compiled by 145 expert authors, states that the rate of global change in nature during the past half century "is unprecedented in human history." It also found that the global rate of species extinction "is already at least tens to hundreds of times higher than the average rate over the past 10 million years and is accelerating."

The report calls for urgent "transformative changes" to reverse the situation and states that direct drivers of change in nature that have the largest global impact are, in order, changes in land and sea use, exploitation of organisms, climate change, pollution, and the invasion of alien species. It warns that the future impacts of climate change on biodiversity and ecosystem functioning are projected to become more pronounced over the coming decades.

Speakers at the briefing said that biodiversity is important to protect not only because species have their own purposes in the ecological web but also because they provide substantial benefits to people.

"If anyone thinks that biodiversity is not crucial to human existence, think again," Udall said, noting that at least 40% of the world's economy is based on biological resources and that the diversity of life provides humanity with food, shelter, medicine, and economic development, among other benefits. "Living ecosystems support us. America's wildlife is in great jeopardy," he said. "We must act now."

No Second Chance After a Species Goes Extinct

Establishing a wildlife corridors system "is something that shouldn't be about party. It should be about just saving our planet," said Rep. Don Beyer (D-Va.), who introduced companion legislation in the House.

Beyer, who is cochair of the New Democrat Coalition's Climate Change Task Force, said that he and cosponsor Rep. Vern Buchanan (R-Fla.) will be working with the House leadership to get the bill on the House calendar. He also said that Rep. Raúl Grijalva (D-Ariz.), chair of the House Committee on Natural

Resources, has indicated that he wants to push this legislation in that committee.

Beyer optimistically stated that he expects "scores of Republican votes when it gets to the House floor." No Republicans had signed on to earlier versions of the bill introduced during previous sessions of Congress, and Buchanan is so far the sole Republican cosponsoring the new legislation.

Raising Concern About Biodiversity

At the briefing, Ron Sutherland, chief scientist with the Wildlands Network, a Seattle, Wash.-based conservation group that supports the legislation, speculated about why concern about biodiversity hasn't yet caught on as a hotter issue in the same way that climate change has.

"One perspective might be that there was a huge push to protect biodiversity for its own sake in the '90s, and I think that that push eventually earned the sort of inevitable fatigue on all the champions for it. Climate change became kind of the new cause, and a lot of young folks have joined into that movement," Sutherland said. "I think we're remembering the fact that we depend on the Earth's biodiversity. Now, pollinators have become such a huge cause lately. So I think that the pendulum is shifting or at least is broadening again, so that there's room again to talk about the other environmental challenges that we're facing. It's not just climate change. It's land use change that is causing a huge threat to biodiversity."

> "We don't get a second chance once a species becomes extinct."

Sutherland noted, "That's where this bill really could help out here in the United States: by helping repair the landscape to help species to survive and also to respond to climate change."

A Political Problem, Not a Scientific Problem

"Human intervention caused this mass extinction crisis. Now human intervention through legislation must reverse the tide," Udall added. "We already know how to address this crisis. This isn't a scientific problem. It's a political one. The science is clear: Corridors help protect our most iconic species."

By **Randy Showstack** (@RandyShowstack), Staff Writer

Tree Rings Record 19th-Century Anthropogenic Climate Change

At some point in the past few hundred years, human activities became a dominant force influencing Earth's climate, affecting natural hazards such as drought. But it's difficult to pinpoint exactly when this tipping point occurred. A new study tracking temperature seasonality—the difference between summer and winter mean temperatures—has found that major indicators of global warming were present as early as 1870.

"It is well known that humans are driving global warming, but when did this begin?" asked Jianping Duan, a paleoclimatologist at the Chinese Academy of Sciences in Beijing and lead author of the study, published in April in *Nature Sustainability* (bit.ly/tibetan-tree). "Our study has shown that anthropogenic influence on climate change started much earlier than the 20th century."

Determining when human activity began "driving global warming" is difficult because instrumental climate records go back only about 100 years. "We need a reference period long enough to judge when anthropogenic climate change began," Duan said.

To reconstruct paleoclimate data for the past 300 years, Duan and his colleagues turned to tree ring records collected on the Tibetan Plateau from trees that can live for more than 300 years.

By measuring the width and density of the trees' rings, the researchers were able to track changes in seasonal temperature fluctuations. They found that temperature seasonality was relatively stable until the 1860s and began decreasing in the 1870s. At that point, winters began getting warmer, closing the temperature gap between the two seasons. Researchers also found evidence supporting the same conclusion in proxy-based seasonal temperature reconstructions in Europe.

The team also used climate model simulations to show that greenhouse gases and aerosols have been the primary drivers of climate change since the late 19th century. "Our study shows that the detectable weakening of temperature seasonality, which started synchronously over the northern mid-high latitudes since the late 19th century, can be attributed to anthropogenic forcing," Duan said.

Models also showed that increased greenhouse gas concentrations are the main contributors over northern high latitudes, whereas sulfate aerosols are the major contributors over northern midlatitudes.

Ancient trees preserve paleoclimate records in the seasonal growth of their rings, which can help scientists reconstruct climate change over the past 300 years. Credit: Mary Caperton Morton

Most paleoclimate studies focus on increasing surface air temperatures, but seasonal temperature fluctuations provide a complementary data set, said Michael Evans, a paleoclimatologist at the University of Maryland in College Park who was not involved in the new study.

"The annual cycle is the largest-amplitude form of variation that we see in our modern climate. It's important to know how that might change and why, as it influences how organisms function within their ecosystems," Evans said. For example, trees may start budding earlier, or migratory birds may fly south later, taking advantage of milder winters.

Previous studies have shown that the annual temperature cycle—calculated as the difference between summer and winter temperature extremes—has been decreasing over the past several decades. The new study is among the first to use paleoclimate records to trace this trend so far back in time.

"The next step will be to see how the decrease in seasonal temperature fluctuations affects our living environment and its impact on agriculture, ecology, and perhaps human health," Duan said.

By **Mary Caperton Morton** (@theblondecoyote), Science Writer

Science in This Century Needs People

In July 1991, the freighter *Tuo Hai* collided with the fishing vessel *Tenyo Maru* off the northern coast of Washington State, resulting in an oil spill that quickly spread to cover hundreds of square kilometers. At the time, I was studying a seabird colony in the path of the spill, and I realized, as the oiled birds began to wash in, that we had no baseline against which to compare the mounting body count. How many wash in normally?

In years of coastal fieldwork, I had already noticed a seasonal uptick in the beaching of my focal species, the common murre, during the summer-fall transition. These deaths were a natural result of the end of the breeding season, when exhausted parents and inept chicks are more likely to die as the winter storm season begins, but I wondered to what degree this normal signal might be influenced by environmental forcing. To address either question, I needed a much larger, longer-term data set on the beaching rate.

At its scientific best, citizen science can create huge, detailed data sets that capture these patterns at local, regional, and even global scales.

I decided to create that data set and in the process founded the Coastal Observation and Seabird Survey Team (COASST). At the time, I was a young faculty member looking for a method of expanding data collection beyond the physical abilities of myself and my team. That mission has evolved over the course of 2 decades into a passion for promoting citizen science as a rigorous method of data collection, fully worthy of being part of the toolbox of mainstream science.

Starting Points

Where seabirds are found across the seascape is directly influenced by the quantity, quality, and predictability of their prey—a table that is set by oceanographic and atmospheric processes operating locally to globally, over days to decades. Seasonal upwelling, decadal climate patterns like the Pacific Decadal Oscillation, and relatively sudden shifts such as an El Niño or a marine heat wave will all influence prey availability, causing birds to choose to move—rightly or wrongly—in search of dinner. Wrong choices result in death, and that drifting carcass will succumb to the wind, currents, and tides. In the Pacific Northwest, the body of a bird that dies within 125 kilometers of shore has a chance of reaching the beach before sinking. Those few carcasses washing ashore have a short shelf life before they are scavenged, buried by the

Science is a team sport at COASST, where teams spread out to search the beach for bird carcasses and rejoin to process each one found. "Handlers" don latex gloves for protection, whereas "pencils" take charge of data recording and checking the field guide. After measuring and photographing, handlers tag a wing with a unique sequence of colored bands that allows COASST to track persistence and leave the carcass in place. Credit: COASST

In the fall of 2016, COASST partners on Saint Paul Island in the Pribilof Islands of Alaska recorded an unprecedented mortality event of the tufted puffin population (shown here are two adult puffins and an adolescent at right). Deteriorating weather conditions forced surveyors from the Aleut Community of St. Paul Island Ecosystem Conservation Office (ACSPI-ECO) to drive the beach in all-terrain vehicles, collecting carcasses and moving them off the beach to a safe location for sorting and photographing. The resultant protocol, known as Die-off Alert, is now taught by ACSPI-ECO and COASST in communities throughout coastal Alaska. Credit: ACSPI-ECO

wind, or washed back out during the next high tide.

Despite these sources of variability, there is a discernible cadence to beaching over time, an annual rhythm that can be tracked by monthly surveys. The most important thing that COASST does is statistically document this regionally specific pattern—the right place, right time, right species baseline—of what birds are expected where and when.

I started COASST with the help of a postdoc who knew far more about ornithology than I did, a grant from the David and Lucile Packard Foundation, and a question: Could we find locals enthusiastic about collecting data on the identity, abundance, and condition of beached birds on an ongoing basis and in a standardized manner? We also needed to design a data collection program that allowed for expert verification of species identity. If these data were ever to be used in mainstream science or in a legal proceeding following an oil spill, they needed to be beyond doubt.

What we came up with is one of the simplest tenets of science: evidence first, deduction second. In our case, the evidence includes classification of the foot type, three specific body measurements, and two photographs with a standard scale. The deduction is lowest taxonomic classification, which can be made with our custom field key, *Beached Birds.*

We started our data collection corps with 12 residents of Ocean Shores, along the southern coast of Washington. COASST today includes around 800 people collecting monthly data on beached birds and another 200 collecting data on marine debris. Our footprint stretches from Mendocino, Calif., to the Canadian border and throughout Alaska. We now work with partners in California (BeachCOMBERS and Beach Watch) and western Canada (British Columbia Beached Bird Survey). That means our data collection currently spans three large marine ecosystems: the California Current, Gulf of Alaska, and eastern Bering Sea, as well as parts of the western Bering Sea and Chukchi Sea.

Unlike citizen science programs that use online training and occasionally rely on self-taught hobbyists, COASST commits to hands-on, in-community trainings designed for beginners. If you can tell it's a bird and it's dead, we can teach you how to "get to species" in a single 5-hour session. And the citizens in our citizen science? They are citizens of the planet, citizens of the ecosystem. We start in new communities when we're invited, and we work with local partners to recruit trainees without questioning their knowledge about birds or their politics. I've trained people in bars, churches, ferries, elementary schools, libraries, malls, tribal headquarters, and senior centers. We currently visit about 80 small coastal communities in a 2-year cycle. And we commit to returning. We constantly communicate with our participants, offering feedback about whether that last carcass they found really was a northern fulmar or sending out the latest information we have about how and why beaching patterns are changing.

> Could we find locals enthusiastic about collecting data on the identity, abundance, and condition of beached birds on an ongoing basis and in a standardized manner?

So, yes, we travel a lot, and, no, citizen science isn't free, nor is it easy. We write grant proposals to support our science just like everybody else, and we push ourselves and our collaborators to get that next paper submitted. We think about what we do and how we can make it better every day.

From Data to People

In the beginning, I was obsessed with data quality and making sure our data collectors were being as accurate as possible. One way we solved that problem was by breaking down the science into component tasks, things like foot type classification and body measurements. Although this approach worked with species identification, our efforts to control the sampling design weren't as successful.

Initially, we created a specific list of sites to be surveyed on the basis of the substrate, orientation, and inclination of the beach. But people wanted to choose "their place" whether our sampling design indicated it was needed or not. It seems impossibly arrogant to me now, thinking back on it, that my starting expectation was that I could waltz into a coastal community and tell people what to do *and that they would do it without question.* That works with undergraduate students and technicians, so why not with everyone else? We now know that what brings people to a training in the first place—a strong attachment to a specific beach and a desire to learn more about that place—was also the reason they politely but firmly refused to be assigned a survey location. COASSTers now choose the beach they want, and over 90% of training attendees sign on to participate.

What I've come to realize is that COASSTers are first and foremost people. If COASST can pique their interests, support their sense of place, provide them with proper training, respond to their questions and concerns, and thus offer them an authentic role on our science team, we are rewarded with a cadre of highly devoted, rigorous, long-term data collectors. The average COASSTer is able to identify the species of a carcass 87% of the time and maintains near-monthly survey frequency for about 3 years.

COASSTers understand their role as both scientific and social: They perform rigorous data collection, communicate to others about

COASST, and recruit community members into the program. They talk to friends and family about their experiences, and they connect with influencers such as resource managers, politicians, and the media to tell them about our research findings. COASSTers embody the saying "Bear witness, take action."

Big Data Citizen Science

Documenting environmental change requires long-term data on where and when natural things happen: earthquakes, extreme weather, the first flowers of spring, dead birds on beaches. At its scientific best, citizen science can create huge, detailed data sets that capture these patterns at local, regional, and even global scales. In COASST, thousands of participants have created a highly accurate, highly rigorous data set that has gone directly into science and resource management.

Our science stories are sobering. We've documented the largest marine bird die-off on record anywhere in the world due to a harmful algal bloom. We've shown that the impact of the largest and longest-lasting marine heat wave the planet has yet experienced included multiple, massive seabird mortality events from California to Alaska. Working with resource management partners, we've co-created a series of annual ecosystem indicators that inform everything from the California Current Integrated Ecosystem Assessment to the annual report to the North Pacific Fishery Management Council. COASST is regularly asked to assist in decision-making on the basis of our data and our expertise: Should the hunting season for marine ducks be opened next week? Do these carcasses present a disease risk to coastal peoples? Should the beaches be closed to tourists? We do science that matters.

If the past century was about expansion of science through technology, this century had better be about expansion through people. Closing the doors of the ivory tower and cloaking ourselves in a language that few can understand won't save science, and it certainly won't save the world.

Expanding our science teams to include everyone with an interest or a need is a scary but exciting thought because as the face of science changes, so will the practice. With a larger and more diverse team, we will ask and answer questions differently. Citizen science is one strand of that braided river of change. And now that I'm in it, I honestly can't imagine why I would ever do things any other way.

A dark gray northern fulmar is one of the top three species recorded by COASST. In addition to noting its shape, COASST participants record the bill measurement—a straight line from tip to "hairline"—on each carcass found. Credit: COASST

By **Julia K. Parrish** (jparrish@uw.edu), University of Washington, Seattle

EOS CENTENNIAL COLLECTION
AGU100 ADVANCING EARTH AND SPACE SCIENCE

Caregiver Awards Support Early-Career Researchers

Last December, scientists—and their families—gathered in Washington, D.C., for AGU's Fall Meeting 2018. Credit: Event Photography of North America Corporation

Last December, several early-career biogeoscientists got some timely assistance at AGU's Fall Meeting 2018. Early-career scientists are often starting families as well as careers, and caregiver responsibilities sometimes present a barrier that can prevent them from fully participating in conferences and obtaining the career benefits of sharing their research and networking with other scientists. These opportunities are critical for early-career researchers who are working to establish their scientific reputation and find jobs in research fields.

AGU's Fall Meeting 2018 served as the official launch of the organization's Centennial celebrations centering around ideas that transform Earth and space science and how we conduct our research. In 2018, the Biogeosciences Early Career Committee saw this as motivation to establish the Early Career Caregiver Award. This award was given to Biogeosciences section early-career members attending Fall Meeting who had extra financial constraints associated with being a primary caregiver for a child or other dependent.

An Opportunity to Meet a Need

In 2018, each AGU section received $5,000 to spend toward early-career programming at Fall Meeting 2018. The Biogeosciences Early Career Committee decided to use a portion of the money to fund awards to early-career members to offset conference attendance costs associated with being a primary caregiver. Such responsibilities can include daycare, hiring a temporary caregiver, covering conference registration costs for a child, or supporting a nonscientific partner's attendance as a caregiver. One recent study showed that 43% of women and 23% of men among new STEM parents left the workforce, switched fields, or transitioned to part-time jobs, suggesting that early-career mothers (and, to a lesser extent, fathers) face challenges as caregivers with STEM careers [*Bernstein,* 2019; *Cech and Blair-Loy,* 2019].

Attending a conference with a child or other dependent brings substantial financial costs, including travel and hotel rooms for the dependent. In addition, without supplemental childcare, a conference attendee may not have the time to participate fully in the conference. Conference organizers face challenges as well as they attempt to support early-career parents and families [*Calisi and a Working Group of Mothers in Science,* 2018]. In particular, early-career mothers face a "baby penalty" that prevents them from enjoying a thriving conference experience. This penalty can be reduced if resources like lactation rooms, affordable on-site childcare, and childcare support are provided.

Without supplemental childcare, a conference attendee may not have the time to participate fully in the conference.

How do science conferences stack up now? The *Science* Careers team from the American Association for the Advancement of Science (AAAS) evaluated 34 conferences in North America in 2018. It determined that 94% provided lactation rooms and 68% provided childcare support, but the percentages are much lower for conferences in physical sciences, mathematics, and computer sciences [*Langin,* 2018]. Although the overall statistics are encouraging, these services are not enough for early-career parents for whom conference attendance requires extensive logistical planning and can be prohibitively expensive [*Grens,* 2017].

Beginnings of a Solution

The Biogeosciences Early Career Committee members (Benjamin Sulman, Aditi Sengupta, Zachary Brown, Melany Ruiz, and Ceth Parker), with help from 2018 section president Ariel Anbar and president-elect Elise Pendall, crafted an award announcement call and solicited applications from Biogeosciences section early-career members who are primary caregivers and were planning to present at Fall Meeting 2018. The announcement was advertised through social media and the Biogeosciences section newsletter.

The committee received 17 applications from early-career scientists ranging from Ph.D. students to assistant professors. The majority of applicants were early-career mothers. The evaluation criteria focused on the applicant's need for support and how the award would improve the applicant's ability to fully participate in the meeting, and the potential of the award to enhance the applicant's career through meeting attendance.

The committee disbursed eight awards of $500 each. Fathers made up 35% of the applicant pool, demonstrating the strides that fathers are making to share caregiver responsibilities. Nevertheless, the applicant pool demonstrated that women still bear the bulk of responsibility for child and dependent care, consistent with a wide body of research [*Jolly et al.,* 2014; *McBride and Mills,* 1993; *Pew Research Center,* 2013; *Yavorsky et al.,* 2015].

Although all of the applicants in 2018 were caregivers of children, the solicitation recognized that early-career members may be caregivers of a disabled or elderly family member. Thus, the awards were open to early-career attendees who were caregivers for any type of dependent rather than being restricted to parents of young children.

Evidence of Success

Many applicants were enthusiastic in pointing out the need for such awards. For example, Kim Novick, an award winner, said, "the support made it easier to ensure my infant had high-quality care while I attended AGU. It also gave me a sense that the AGU Biogeosciences section valued my dual roles as a scientist and a parent to young children."

As one of the awardees, Mary Whelan, points out, there is a lack of institutional and cultural support to childbirth and subsequent care of young children, "with the awards serving as a way to retain a productive STEM workforce by supporting their personal life choices while enhancing their professional development."

Caregiver awards and resources are critical to encouraging women and men to stay in scientific fields through their children's early years and provide shared experiences as a family, as noted by another awardee, Audrey Taylor.

Following the announcement of the awards, the Biogeosciences section and the Early Career Committee received phenomenal support and kind words from many early-career and late-career members. They reaffirmed that the awards supported inclusion and the success of early-career researchers whose responsibilities as caregivers currently pose challenges to their professional growth.

Building on Our Success

In addition to travel grants, we suggest broader efforts to support caregivers at the Fall Meeting. These efforts could include supporting facilities like lactation rooms, providing lockers or other spaces to parents to store caregiver-associated supplies, subsidizing on-site childcare costs for early-career attendees, reducing registration fees for supporting family members, and seeking additional sponsorship-based funding. Furthermore, we believe that it is essential for this program to develop a stronger and more stable base of financial support, rather than requiring individual sections to allocate ad hoc early-career funding. Support at the AGU level would allow the program to maintain long-term continuity as well as open it to conference attendees from multiple sections.

In addition to offering direct assistance to early-career conference attendees, another goal of the awards was to encourage other sections and AGU as a whole to support early-career members. We propose a society-wide change in which all sections unite to promote diverse representation by supporting early-career members as they balance their professional and caregiver responsibilities.

As a scientific community, if we truly are to stand for inclusive excellence and transformative science, it is imperative that we strive to support our members and welcome their identities. As AGU celebrates its Centennial and looks forward to an exciting time in advancing Earth and space science research, supporting early-career members in their dual roles as caregivers and researchers will send a message of an inclusive and welcoming scientific society.

Acknowledgments

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Children of attendees at AGU's Fall Meeting 2015 enjoy activities at Exploration Station. Credit: Karna Kurata/ www.garywagnerphotos.com

Audrey Taylor, one of the award recipients, with her daughter on her way to AGU's Fall Meeting 2018. Credit: Photo provided with permission from Audrey Taylor

References

Bernstein, R. (2019), After a baby, 28% of new parents leave full-time STEM work, *Science,* https://doi.org/10.1126/science.caredit.aax0346.

Calisi, R. M., and a Working Group of Mothers in Science (2018), Opinion: How to tackle the childcare-conference conundrum, *Proc. Natl. Acad. Sci. U. S. A., 115*(12), 2,845–2,849, https://doi.org/10.1073/pnas.1803153115.

Cech, E. A., and M. Blair-Loy (2019), The changing career trajectories of new parents in STEM, *Proc. Natl. Acad. Sci. U. S. A., 116*(10), 4,182–4,187, https://doi.org/10.1073/pnas.1810862116.

Grens, K. (2017), Baby on board, *Scientist,* 1 Sept., https://www.the-scientist.com/careers/baby-on-board-30991.

Jolly, S., et al. (2014), Gender differences in time spent on parenting and domestic responsibilities by high-achieving young physician-researchers, *Ann. Intern. Med., 160*(5), 344–353, https://doi.org/10.7326/M13-0974.

Langin, K. (2018), Are conferences providing enough child care support? We decided to find out, *Science,* https://doi.org/10.1126/science.caredit.aaw3741.

McBride, B. A., and G. Mills (1993), A comparison of mother and father involvement with their preschool age children, *Early Child. Res. Q., 8*(4), 457–477, https://doi.org/10.1016/S0885-2006(05)80080-8.

Pew Research Center (2013), Modern parenthood: Roles of moms and dads converge as they balance work and family, Washington, D.C., www.pewsocialtrends.org/2013/03/14/modern-parenthood-roles-of-moms-and-dads-converge-as-they-balance-work-and-family/.

Yavorsky, J. E., C. M. K. Dush, and S. J. Schoppe-Sullivan (2015), The production of inequality: The gender division of labor across the transition to parenthood, *J. Marriage Family, 77*(3), 662–679, https://doi.org/10.1111/jomf.12189.

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APOLLO'S LEGACY

50 Years of Lunar Geology

Samples of the Moon's surface brought back by Apollo astronauts ushered in a new era of planetary science. Scientists today continue the legacy.

By Kimberly M. S. Cartier

Apollo 15 astronaut James Irwin collects samples near the eastern rim of Imbrium Basin, not far from the lunar roving vehicle (opposite), with the lunar module in the background. Credit: NASA/Lunar and Planetary Institute

EOS CENTENNIAL COLLECTION

July 20, 1969, will forever be carved into the history books: the day that humankind took its first small step into the cosmos. The dawn of a new scientific era came just 4 days later.

When Apollo 11 splashed down on 24 July, planetary scientists knew they would soon get their hands on the first samples of material brought back from the surface of the Moon.

Apollo 11 astronauts brought back a scant 22 kilograms of material for scientists to study. Each subsequent Apollo mission—except Apollo 13, of course—brought back more and more rocks, soil samples, and drill cores. All told, the Apollo astronauts carried back to Earth 382 kilograms from six different areas of the Moon's surface, each sample stored in a container that preserved a Moon-like environment.

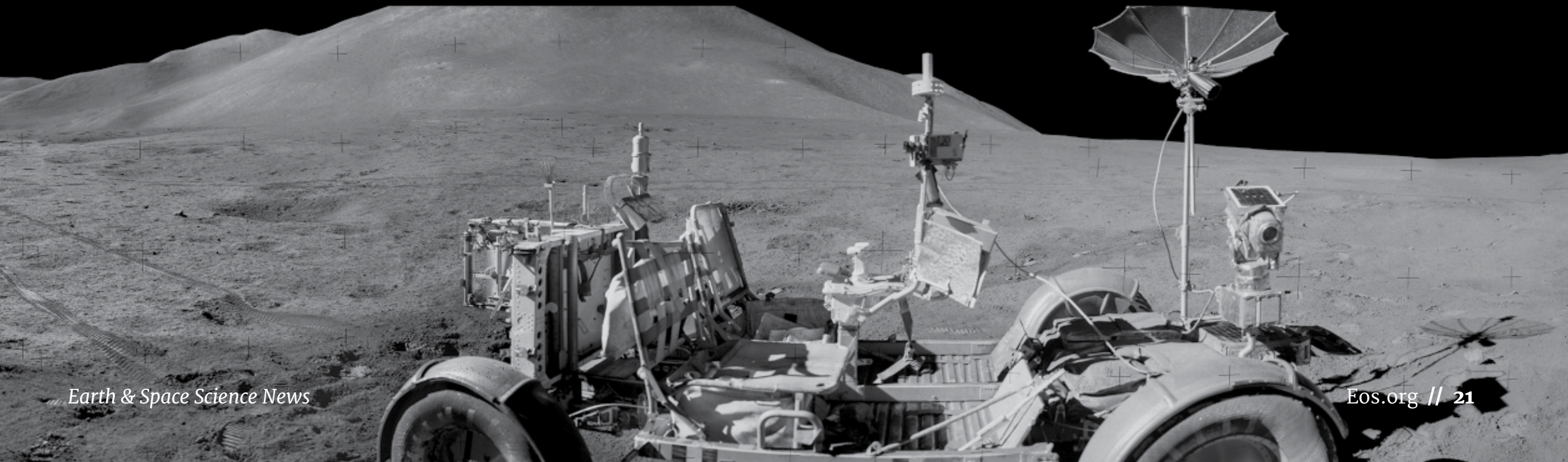
The initial impressions of the Apollo samples proved for the first time some facts about the Moon that may seem obvious today: There is not now and there likely never has been life on the Moon; meteor impacts throughout the Moon's history have pulverized the surface; and the Moon and Earth share many geochemical similarities.

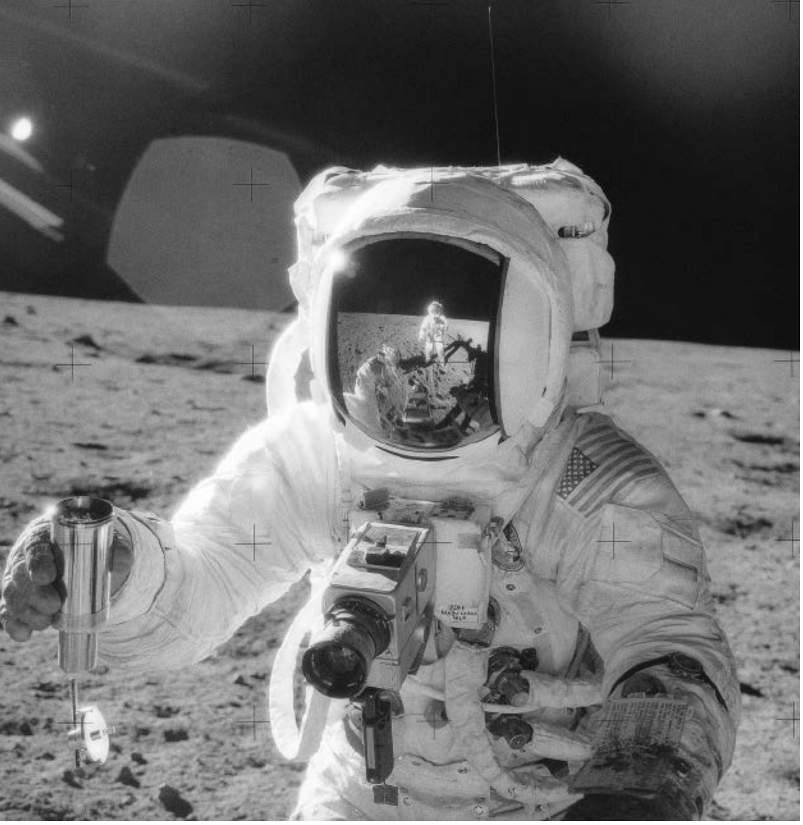
But technology, computer power, and scientific knowledge have grown exponentially since humans last stepped foot on the Moon in 1972. Thanks to the foresight of NASA leaders of the time, some of the Apollo samples were curated so that future scientists could study pieces of the Moon that hadn't been exposed to Earth's atmosphere.

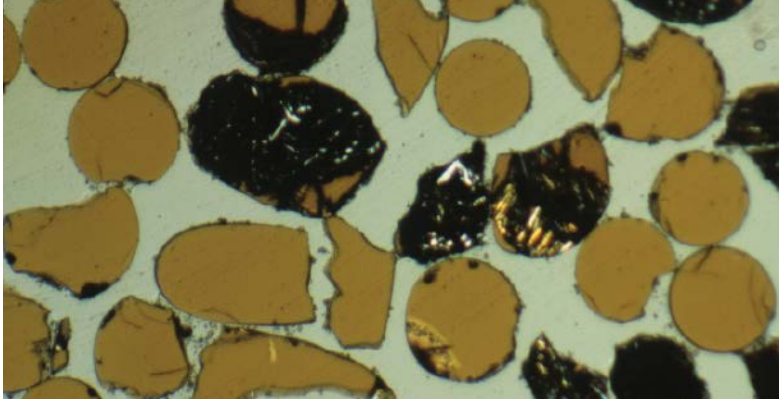
"What we like to say is that sample return missions allow scientists not yet born to use instruments not yet developed to answer questions not yet asked," Jamie Elsila, an astrochemist at NASA Goddard Space Flight Center in Greenbelt, Md., told *Eos.*

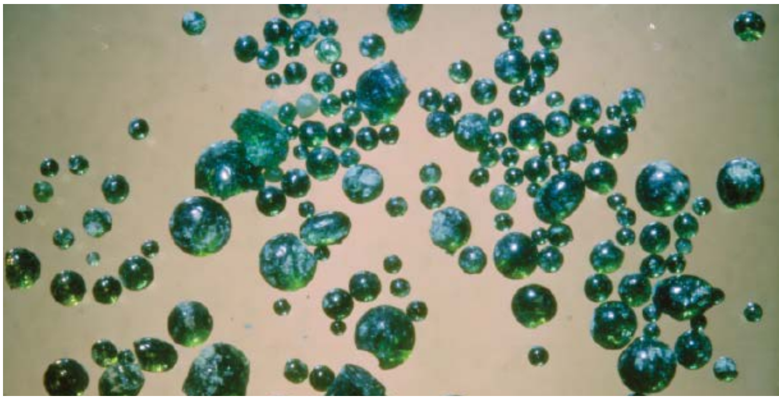
Today "we're asking some of the same questions that the scientists back then were asking," Elsila said. "Because [NASA] preserved these samples and curated them carefully, now we're able to go back and try to answer these questions."

As post-Apollo scientists studied carefully doled-out lunar samples, they discovered much more about the









Left: Apollo 12 astronauts collected 34 kilograms of soil and rocks from the Moon's surface that they brought back to Earth for scientists to study. Seen here, Alan Bean holds up a filled sample tube during an extravehicular activity on 20 November 1969. Charles "Pete" Conrad is reflected in his visor. Top right: Lunar sample 74220 contains orange soil discovered near Taurus-Littrow Valley during the Apollo 17 mission. A 2.1-millimeter-wide thin section of some of the glass is seen here in transmitted light. Bottom right: Apollo 15 astronauts brought back regolith samples that included clods of green soil. Within the soil were small spheres of green volcanic glass, like these that were found in sample 15426. Credits, clockwise from left: NASA/Marshall Space Flight Center; D. Kring/NASA/Lunar and Planetary Institute; NASA/Johnson Space Center, Lunar and Planetary Institute

Moon and its history than scientists of the 1970s could have. Here are some of the most notable discoveries about our celestial neighbor that have come from Apollo samples over the past 50 years.

The Rough Life of Lunar Regolith

Life as a soil grain on the lunar surface is tough. Nowadays it's rare for a large impact to happen on the Moon, but microscopic impacts happen all the time.

"The lunar regolith is being bombarded by micrometeorites and high-energy particles from the solar wind," explained Richard Walroth, an instrument developer at NASA Ames Research Center in Mountain View, Calif.

Earth's atmosphere protects its surface from these microscopic hits. On the airless Moon, however, tiny meteorites, cosmic rays, and superfast ions from the Sun constantly strike the surface. This process, called space weathering, makes the lunar regolith literally rough around the edges.

"The grains melt at the very edge and form things called agglutinates," Walroth said, which are mineral fragments fused together by glass. "They also get a little nanophase iron too. They're like nanoscale droplets, essentially of metallic iron in glass."

Walroth and his team have developed instruments to look at the mineralogy and weathering of agglutinates and other Apollo samples.

The samples returned by Apollo astronauts bear the scars of space weathering, but some of the regolith samples were shielded from one type of weathering for millions of years.

"Shadowed soils…were collected at the surface but underneath the overhangs of boulders," said Barbara Cohen, a planetary scientist at NASA Goddard Space Flight Center. "In that case, we think that they were shadowed from things like micrometeorite impacts, but they were still exposed sometimes over seasonal and day-and-night cycles to things like solar wind."

"They might have a different total exposure history" than soils that were exposed to all types of space weathering processes, Cohen said. Comparing soils collected in different places will help Cohen and her team tease out which processes cause the different weathering signatures they see in Apollo samples.

"Space weathering is a global process," Walroth said, but "every part of the Moon's going to get affected by it a little bit differently."

Something Old, Something Slightly Less Old

It turns out that lunar rocks become discolored as they age, and close-up study of the Apollo samples helped explain why.

"Space weathering is a really complex set of processes that affect these grains very much at the nanoscale," Katherine Burgess, a geologist at the U.S. Naval Research Laboratory in Washington, D.C., told *Eos*. Burgess uses transmission electron microscopy to study how weathering chemically alters the surfaces of planetary bodies.

Space weathering processes "have huge impacts in how planetary bodies look spectroscopically from spacecraft and telescopes and change their optical properties," she explained. "That's generally referred to as reddening or darkening."

By studying the Apollo samples over the past 50 years, "we've figured out that the main cause of these optical changes is the formation of [nanophase iron] rims that

are up to a couple of hundred nanometers thick," Burgess said.

How much a grain has been altered by weathering processes can tell researchers how long it was left exposed on the surface. This is key to understanding the Moon's geologic history and how long it takes for surface rocks to be buried underground.

"You know, we say that Neil Armstrong's boot prints will be there forever," Walroth said, "but in reality, they are eventually going to be buried by all the regolith. It'll just take a long time."

What's become clear to lunar geologists is that apart from large and small meteorite impacts that churn up the regolith, the Moon's surface is still aging, just very slowly. "These are processes that take place over millions of years," he said.

Change on the (Solar) Wind

Space weathering does more than just rough up the lunar regolith, said planetary geologist Natalie Curran. It can also change the regolith's composition.

"Cosmic rays from outside of the solar system produce noble gases in these samples," said Curran, who works at NASA Goddard Space Flight Center. "The cosmic rays basically interact with elements in the rock—so things like oxygen, silicon, or magnesium—and they form actual noble gases."

"There were very relatively low abundances of noble gases in the rock to start with," she said, because the Moon's original stock of volatile gases is long lost to space. "So the more exposed to the space environment and the more cosmic rays hit that sample, the more isotopes of noble gases are produced."

The Sun, too, has its own noble gases to impart to the Moon's surface through the solar wind.

Solar wind noble gases "get implanted into the surface of these very, very small grains, and they have a different isotope ratio to what the cosmic ray–produced noble gases have," Curran said. "So we can measure all these noble gases in a sample and then look at the different isotopes to see which noble gas is produced from each of the different reservoirs."

Noble gas analysis is another way that scientists can learn more about the signatures of different space weathering processes. Curran and Cohen are working to do just that.

"We're interested in seeing the differences between things that are completely exposed all the time and these things that were partially eclipsed by boulders at some point in their history," Cohen said. "If some effects shut off and others keep going, then we would be able to say, 'Oh, that's what the signature of this other effect looks like.'"

> "Returned samples are an investment in the future."

Glass, Glass Everywhere

The lunar surface might seem to be all shades of gray, but that's definitely not the case everywhere on the Moon. Apollo 17 astronauts Harrison Schmitt and Eugene Cernan and CapCom Robert Parker learned this firsthand. Here's a short excerpt from a recording of the moment of discovery:

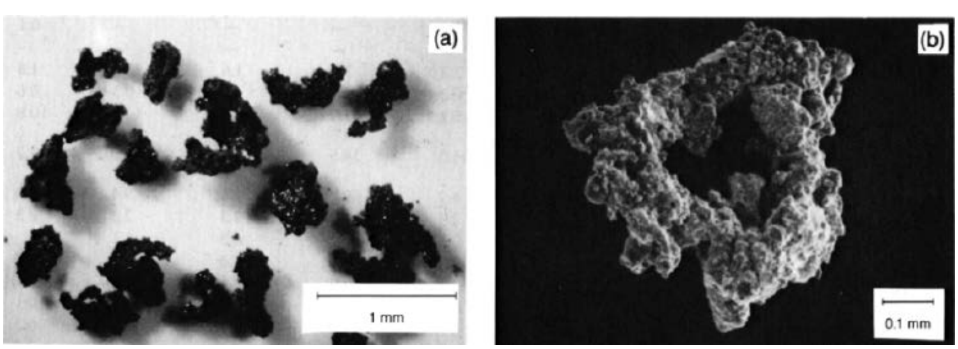
Schmitt: *It's all over! Orange!*
Cernan: *Don't move it until I see it.*
Schmitt: *I stirred it up with my feet.*
Cernan: *Hey, it is! I can see it from here!*
Schmitt: *It's orange!*
Cernan: *Wait a minute, let me put my visor up. It's still orange!*
Schmitt: *Sure it is! Crazy!*
Cernan: *Orange!*
Schmitt: *I've got to dig a trench, Houston.*
Parker: *Copy that. I guess we'd better work fast.*
Cernan: *Hey, he's not going out of his wits. It really is.*
Parker: *Is it the same color as cheese?*

The orange soil is actually a deposit of microscopic orange glass mixed with the beige-gray regolith. These glass beads formed when ancient lunar "fire fountains" belched up molten magma, some of which condensed into droplets of pyroclastic glass and rained down onto the lunar surface 3.5 billion years ago.

"What most people don't realize is that the soil on the Moon is about 20% glass beads" in the areas we've sampled, Darby Dyar, a planetary scientist at Mount Holyoke College in South Hadley, Mass., told *Eos*. Dyar, also at the Planetary Science Institute in Tucson, Ariz., has been studying lunar glass beads since she was in graduate school.

Apollo 15 samples contained similar glass beads that were tinted green. "What you see is, there's about 5% to 20% of these little rounded glass beads which come from the volcanic glass fire fountains," she said.

"The lunar soil is really fascinating in and of itself. The little glass beads are just one component of a really fascinating material," Dyar said.



These typical lunar soil agglutinates are from Apollo 11 lunar sample 10084. (a) NASA photo S69-54827, an optical microscope photograph of a number of agglutinates with a variety of irregular shapes. (b) NASA photo S87-38812, a scanning electron photomicrograph of a ring-shaped agglutinate with a glassy surface coated with small soil fragments. Credit: The Lunar Sourcebook, *via Lunar and Planetary Institute*

No Water Above, but Traces Below

"At the time the Apollo samples came back," Dyar said, "the techniques that we had to analyze them at that time indicated…that there was absolutely no water on the Moon. Certainly, no hydrous minerals, you know, no micas, no clay minerals, no amphibole." On Earth, these minerals form in the presence of water.

Other tests for lunar water looked at the ratios of different iron molecules. "That tells us something about how much oxygen was around when these materials formed," she explained.

In a water-poor environment, iron will usually lose two electrons and exist in ferrous minerals, which are considered reduced. If there is any water around, that water can steal a third electron and create ferric compounds, which are oxidized.

"By 1980, the dogma was that the Moon was both completely dry and completely reduced," Dyar said.

More advanced techniques and more sensitive instruments changed that dogma. Close looks into the volcanic glass beads found that they contain signatures of water, something that has been recently confirmed. And recent research has found that ionized hydrogen from the solar wind creates trace amounts of water in the lunar regolith.

"In the last decade, we're suddenly revolutionizing our idea about what the interior of the Moon looks like," Dyar said. "It looks like it might actually have had, at the time these were erupted, significant amounts of both water and oxygen around. That's quite paradigm shifting."

> "In the last decade, we're suddenly revolutionizing our idea about what the interior of the Moon looks like."

Amino Acids from Afar

"When the Apollo astronauts first brought these samples back," Elsila said, "there was a lot of interest in understanding amino acids and potential organic compounds relevant to life in these samples."

Although it is still unclear how life began on Earth, scientists thought it possible that the collision that formed the Moon out of Earth's crust and mantle also could have transferred the building blocks of life to the Moon.

"In the 1970s, there were a lot of studies looking for amino acids in lunar samples, and they were detected, but the origins weren't able to be determined at that point," Elsila said. There were fierce debates about whether the amino acids were really from the Moon or from accidental contamination.

A few years ago, Elsila led a team that reexamined amino acids in Apollo 16 and Apollo 17 samples to pinpoint their origins.

"We found that they were probably a combination of terrestrial contamination just from the sampling process and the curation process," Elsila said, "but also some amino acids that seem to be indigenous to the lunar surface." Lunar amino acids have a molecular structure distinctly different from terrestrial ones, her team found.

How did those amino acids get there? "The ones we found are similar to amino acids that we've detected in meteorites and other extraterrestrial materials that have probably undergone abiotic chemistry," Elsila said.

Meteorites might have implanted those amino acids on the Moon long ago. Alternately, Elsila said, the molecules' precursors might have blown in on the solar wind and undergone abiotic chemistry to form amino acids. Comparing lunar amino acids from areas exposed to impacts but not the solar wind and vice versa could help solve that mystery.

Investing in the Future

In the next few months, NASA will give scientists access to some never-before-studied Apollo samples. Those samples have never tasted Earth's atmosphere. They've been kept in the same condition they were in when Apollo astronauts brought them back almost 50 years ago.

"Returned samples are an investment in the future," said Lori Glaze, acting director of NASA's Planetary Science Division in Washington, D.C. "These samples were deliberately saved so we can take advantage of today's more advanced and sophisticated technology to answer questions we didn't know we needed to ask."

The research teams NASA selected to look at the samples will work with one another to create a holistic view of the Moon's geologic history as told by the Apollo program. Many of the necessary tests will change those samples forever. But lunar geologists are already looking toward future exploration and future sample return missions to answer our lingering questions about the Moon.

"Unless you're willing to put a rock on the lunar surface and wait a billion years," Walroth said, "it's going to be really hard to answer those questions. But that's why we hope to get material from more and more places around the Moon."

"Our Apollo samples all came from the nearside equatorial region," Cohen said. "We didn't have the context, the global context for them at the time that we sent those missions and got those rocks back. And so saying that we've really sampled the Moon, well, we really have only sampled a very small part of it."

"There are lots of places left to go," she said.

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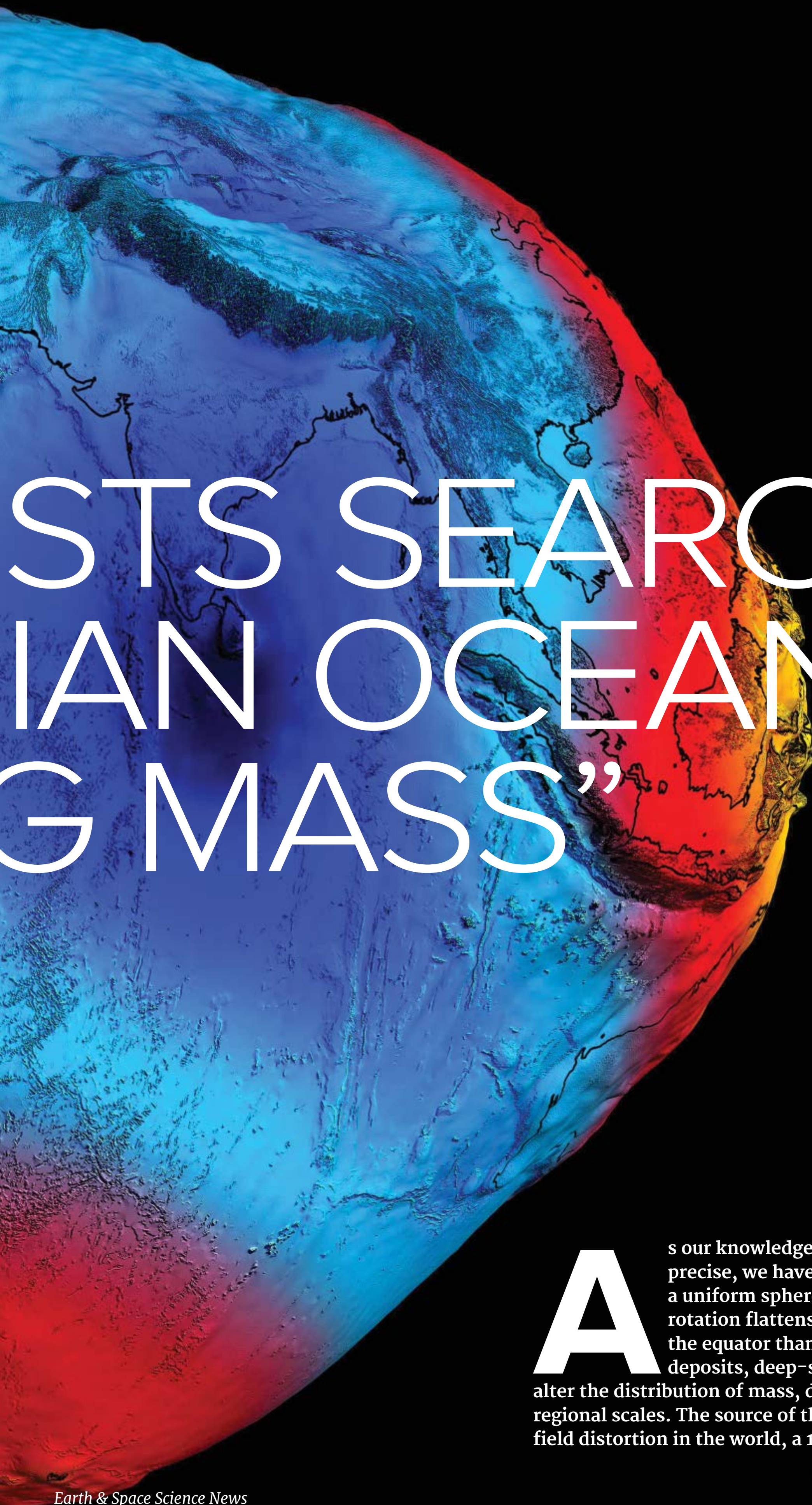
AGU 100
ADVANCING EARTH AND SPACE SCIENCE

SEISMOLOGI
FOR THE IND
“MISSING

By Lachit S. Ningthoujam, Sanjay S. Negi, and Dhananjai K. Pandey

A “dent” in Earth’s geoid (purple), covering a large area in the Indian Ocean, indicates that less of Earth’s mass is concentrated in this area than is typical of other areas. One research team deployed seismic sensors in this area last year to find out why. Credit: ESA/HPF/DLR

STS SEARCH IAN OCEAN'S G MASS”



As our knowledge of Earth's geometry has become more precise, we have come to realize that our planet is not a uniform sphere, as was previously believed. Earth's rotation flattens it into an ellipsoid that is wider around the equator than around the poles. Heavy mineral deposits, deep-sea trenches, and magma reservoirs alter the distribution of mass, distorting Earth's gravitational field on regional scales. The source of the largest equipotential gravitational field distortion in the world, a 106-meter anomaly in the Indian Ocean,

remains a mystery, so an Indian research group went to sea last year to gather clues.

One way of describing Earth's irregular shape is as a geoid, a hypothetical equipotential surface. That is, the geoid is what the shape of Earth's surface would be if oceans covered the whole planet and there were no winds and tides to ruffle the surface—just Earth's rotation and the forces of gravity. Regional deviations of the geoid from an idealized hydrostatic ellipsoid, known as geoid anomalies, can be high geoid (positive) or low geoid (negative). Positive anomalies indicate a dense concentration of mass, like recently subducted oceanic slab. Negative anomalies indicate regions of less dense materials—a reservoir of hot magma, for example—beneath the surface. Extreme geoid anomalies are interesting because they imply a significant shift in the subsurface geodynamic conditions.

Geophysical studies over the past few decades have found an extremely low geoid anomaly in the Indian Ocean. This low-gravity region, which shows up as a 106-meter "dent" in the geoid, is referred to as the Indian Ocean Geoid Low (IOGL) [*Sreejith et al.,* 2013; *Ghosh et al.,* 2017]. Why is Earth's mass in this region so low? The dominant hypotheses are based on seismological investigations [*Čadek and Fleitout,* 2006; *Reiss et al.,* 2017] and viscoelastic modeling [*Ghosh et al.,* 2017]. However, because of inherent methodological limitations and an almost complete lack of offshore seismological observations from this region, the mystery of this perplexing anomaly remains unsolved.

Last year, a research team at the National Centre for Polar and Ocean Research (NCPOR) in India led an extensive long-term deployment of broadband ocean bottom seismometers (OBSs) in the IOGL region to study the geoid anomaly.

Hypotheses and Theories

The low-geoid estimates in the Indian Ocean span a vast area to the south of the Indian subcontinent. Mathematically speaking, these estimates are dominated by very long wavelength (>3,000-kilometer) anomaly components [*Sreejith et al.,* 2013]. The most plausible explanation so far is that anomalous lower mantle convection, weakly coupled to shallow crustal plate motions, causes the large geoidal undulations [*Chase,* 1979].

Because of an almost complete lack of offshore seismological observations from this region, the mystery of this perplexing anomaly remains unsolved.

Previous researchers have put forth several distinct theories underlying the IOGL's existence. These include structural undulation in the core-mantle boundary [*Negi et al.,* 1987], seismic low-velocity anomalies in the upper mantle [*Rao and Kumar,* 2014], and subducted slabs of oceanic origin that collected in a "slab graveyard" in the lower mantle during the Mesozoic era [*Spasojevic et al.,* 2010; *Simmons et al.,* 2015].

Numerical modeling supported by global seismic tomography results provides new insight into the possible source

The scientific team deploys an ocean bottom seismometer (OBS) from the deck of ocean research vessel Sagar Kanya. *Credit: Rahul Mavi*

and the mantle geodynamics beneath the Indian Ocean [*Ghosh et al.,* 2017]. This model shows a low-density anomaly between the upper and middle mantle (~300–900 kilometers in depth) that migrates from an African deep mantle plume toward the northeast, driven by movement of the Indian tectonic plate.

Another view indirectly relates the geoid anomalies to intraplate deformation zones that are a surface manifestation of the mantle convection processes. These zones, which include the Central Indian Ocean Deformation Zone between the Indian and Australian plates, are associated with large-scale faults, folds, high heat flow, and seismic activity [*Mishra,* 2014]. Whether these intense deformation zones within the lithosphere really contribute to such a large-wavelength geoid anomaly is still under debate.

Considering these hypotheses and the broad nature of the anomaly, the IOGL could be a response to an extended mass anomaly with multiple sources. Therefore, local and regional seismic velocity models become critically important to highlight the multiple wavelength sources of this colossal geoid anomaly in the Indian Ocean.

Imaging Deep Structures Beneath the Indian Ocean

To understand and narrow down the gap between the dynamics of materials beneath the surface and its surface manifestation as the IOGL geoid anomaly, NCPOR started a large-scale seismological array deployment in the Indian Ocean. As a pilot project, in May 2018, NCPOR deployed 17 passive broadband OBSs. These sensors recorded continuous time series data of seismic events for 1 year. The array extends laterally from the middle of the nearly circular IOGL anomaly to its southern extent (Figure 1).

The stations are spaced approximately 100 kilometers apart along the OBS profile. The OBS systems are equipped with four-component sensors (one in the vertical direction, two in the horizontal direction, and a hydrophone)

and a digitizer with a dynamic range of −3 decibel points at 120 seconds, taking 100 samples per second.

Our Focus and Potential Applications

The prime objective of our experiment is to image the deep mantle structures and their relationship with the geoid low anomaly in the Indian Ocean. We hope to explain the key factors that make the Indian Ocean geoid anomaly different from geoid anomalies in other parts of the world. Such findings would offer several types of opportunities to geoscientists researching deep-ocean mantle dynamics.

For example, the ancient Tethys Ocean began to close as the Indian continent separated from the African, Antarctic, and Australian continents during the Late Cretaceous to early Paleocene, leading to the opening of the Indian Ocean. Researchers believe that during this period, slabs of oceanic origin subducted into a slab graveyard in the lower mantle [*Spasojevic et al.,* 2010], which possibly contributed to the IOGL. We hope that the seismological data from the OBSs in the Indian Ocean will be able to resolve the uncertainties associated with the hypothesis that the subducted Tethyan plate was seized beneath the Indian plate.

We foresee that seismological data acquired during the deployment period of our project will not only benefit the researchers working in solid Earth science beneath the unexplored parts of oceanic plates but also help to quantify deep-ocean wave dynamics. For example, a research group at the Institut de Physique du Globe de Paris in France is currently attempting to extract signals from seismic network data that could model ocean wave dynamics using a beam-forming approach.

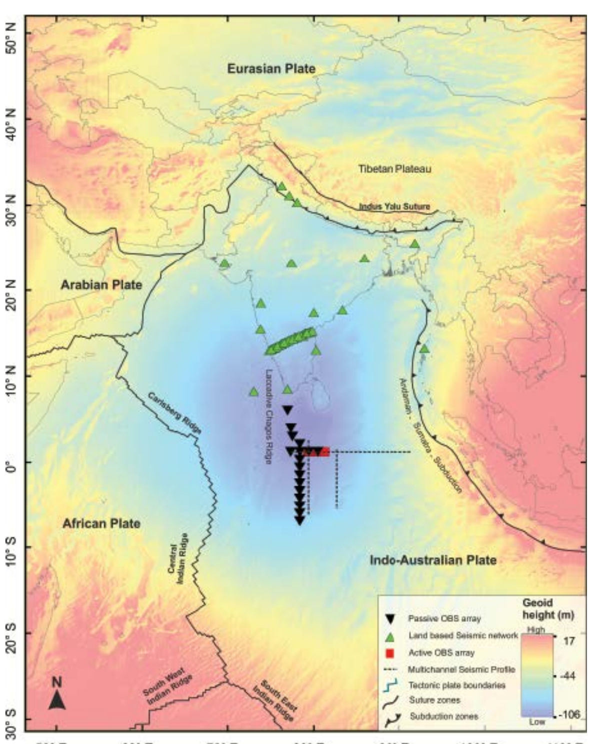


Fig. 1. An OBS array (black triangles) was deployed in a large geoid anomaly (blue area) in the Indian Ocean in May 2018. Black lines represent major tectonic boundaries. Green triangles and red squares represent other regional seismological stations around the IOGL region.

The U.S. Geological Survey (USGS) Global Seismographic Network shows 290 earthquakes with magnitudes of 5.5 or greater recorded between May and December 2018 within an arc distance of 20°–120° from the center of the OBS array that we deployed in May 2018. We are using these earthquakes to model the theoretical ray paths between sources and stations. Modeling theoretical ray paths gives quite a good sense of the resolution we can expect using teleseismic earthquake data from this experiment (Figure 2). Local earthquakes are not common in the central Indian Ocean, but with the help of our OBS array, we might be able to look into the local seismicity around the IOGL region.

The seismological data retrieved from the IOGL experiment will be under an embargo for 3 years. After that, they will be made available to the geoscience community on request through the portal of India's National Centre for Seismology.

Acknowledgments

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References

Čadek, O., and L. Fleitout (2006), Effect of lateral viscosity variations in the core–mantle boundary region on predictions of the long-wavelength geoid, *Stud. Geophys. Geod., 50,* 217–232, https://doi.org/10.1007/s11200-006-0013-0.

Chase, C. G. (1979), Subduction, the geoid, and lower mantle convection, *Nature, 282,* 464–468, https://doi.org/10.1038/282464a0.

Ghosh, A., G. Thyagarajulu, and B. Steinberger (2017), The importance of upper mantle heterogeneity in generating the Indian Ocean Geoid Low, *Geophys. Res. Lett., 44,* 9,707–9,715, https://doi.org/10.1002/2017GL075392.

Mishra, D. C. (2014), Geoid low and highs of the Indian Ocean and western Pacific: Implications to mantle convection, *J. Asian Earth Sci., 79,* 441–445, https://doi.org/10.1016/j.jseaes.2013.10.020.

Negi, J. G., N. K. Thakur, and P. K. Agrawal (1987), Can depression of the core–mantle interface cause coincident Magsat and geoidal 'lows' of the central Indian Ocean?, *Phys. Earth Planet. Inter., 45,* 68–74, https://doi.org/10.1016/0031-9201(87)90198-1.

Rao, B. P., and M. R. Kumar (2014), Seismic evidence for slab graveyards atop the core mantle boundary beneath the Indian Ocean Geoid Low, *Phys. Earth Planet. Inter., 236,* 52–59, https://doi.org/10.1016/j.pepi.2014.08.005.

Reiss, A. S., et al. (2017), A hot midmantle anomaly in the area of the Indian Ocean Geoid Low, *Geophys. Res. Lett., 44,* 6,702–6,711, https://doi.org/10.1002/2017GL073440.

Simmons, N. A., et al. (2015), Evidence for long-lived subduction of an ancient tectonic plate beneath the southern Indian Ocean, *Geophys. Res. Lett., 42,* 9,270–9,278, https://doi.org/10.1002/2015GL066237.

Spasojevic, S., M. Gurnis, and R. Sutherland (2010), Mantle upwellings above slab graveyards linked to the global geoid lows, *Nat. Geosci., 3,* 435–438, https://doi.org/10.1038/ngeo855.

Sreejith, K. M., et al. (2013), High-resolution residual geoid and gravity anomaly data of the northern Indian Ocean—An input to geological understanding, *J. Asian Earth Sci., 62,* 616–626, https://doi.org/10.1016/j.jseaes.2012.11.010.

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Robots Underground

By Adityarup Chakravorty

From exploring flooded sites to providing alerts, robotics is changing the mining industry.

December 2018, Slovenia: A team of scientists, engineers, and technicians from a consortium of universities, organizations, and companies across Europe boldly prepares a robot to go where no robot has gone before.

The robot, UX-1, is prepped to enter and navigate the narrow, flooded passages of the Idrija mercury mine in western Slovenia. It's a field test—UX-1's second—to determine whether the robot can autonomously navigate the dark, murky waters of the closed mine and use its multispectral camera to recognize different minerals.

UX-1's creators hope that one day it will be part of a multirobot platform called the Underwater Explorer for Flooded Mines (UNEXMiN) and be used for "non-invasive [and] autonomous 3D mine mapping for gathering valuable geological, mineralogical and spatial information...that cannot be obtained by any other ways, without major costs," according to the project's website.

UNEXMiN is just one example of several efforts across Europe, and the world, to develop robots and related technology for use in and around mines to perform a variety of tasks—from mapping flooded passages to analyzing mineral concentrations and from increasing operational efficiency to ensuring the safety of people who work in the mining industry.

Exploring Flooded Mines for Minerals

Part of the UNEXMiN project includes identifying closed or abandoned mines in Europe that are now flooded. So far, the Inventory of Flooded Mines lists more than 8,500 such sites. A major thrust for exploring these flooded mines comes from the European Union's policy on raw materials, which has a goal of "fostering [a] sustainable supply of raw materials from European sources."

Using UNEXMiN, which is funded by a European Union program called Horizon 2020, researchers such as Norbert Zajzon, a geologist at the University of Miskolc in Hungary, hope to be able to "reevaluate [these] abandoned mines for their mineral potential, with reduced exploration costs and increased investment security for any future mining operations."

One reason to revisit old, abandoned mines is that "many newer technologies need different [mineral] elements," Zajzon said. Minerals that may not have been valuable or useful in the past may be indispensable for some modern industries.

Take, for example, a set of minerals called the rare earth elements. These are a set of 15–17 metals that usually occur in the same ore deposits and are not particularly rare—they are just dispersed throughout Earth's crust and occur in deposits only rarely at high concentrations.

Over the past few decades, global demand for rare earth elements has skyrocketed. Several are an integral part of many modern technologies, including smartphones and some kinds of computer hard drives; light-emitting diodes (LEDs) that power flat-screen TVs, computer screens, and electronic displays; and defense and clean energy systems, such as wind turbines and hybrid vehicles.

Since the 1990s, China has produced between 85% and 95% of the global supply of rare earth elements. In 2009, China announced curbs on exports of rare earth elements

(citing domestic needs), which, combined with an unrelated political standoff with Japan in 2010, resulted in skyrocketing prices. It was around this time that the European Union developed its policy of exploring and developing domestic sources of minerals, including rare earth elements.

Challenges Exploring Abandoned Mines

Determining which flooded mines may contain deposits of rare earth elements or other valuable minerals is a big challenge, Zajzon said. It would be incredibly dangerous for human divers to enter, navigate, and explore the flooded tunnels and murky waters. It's also a complicated and lengthy process to design a robot that can successfully do so.

Among the many difficulties associated with exploring flooded mines are having to navigate in confined spaces with extremely limited visibility and the need to pack a lot of instrumentation into a relatively small robot; for example, UX-1 is a sphere about 0.6 meter in diameter.

Also, "if something goes wrong, you can't just abort the mission," Zajzon said. "In other underwater scenarios—such as in deep-sea mining—you can just let the robot surface, but you can't do that in a mine!"

To overcome the many challenges of operating in flooded mines, the robots designed as part of UNEXMiN "will employ components such as acoustic cameras, SONAR (Sound Navigation And Ranging), thrusters, laser-scanners, a computer, rechargeable batteries, pendulum, buoyancy control system and a protective pressure hull," write UNEXMiN researchers in a recent paper. These components make up different subsystems, including a propulsion system, a power supply system, a computer system (especially critical because the UNEXMiN robots are designed to be autonomous), and a scientific system with which the robot will be able to take spectral readings of the mine environment and collect water samples.

Building and testing the robot is a highly iterative process, Zajzon said. "First, we built the robot in plastic, then we tested whether a spherical robot could be maneuvered with the thrusters we had. With those results, we proceeded to test the software, first without water, then with water, then with different sensors, and so on."

> Using UNEXMiN, researchers hope to be able to "reevaluate [these] abandoned mines for their mineral potential, with reduced exploration costs and increased investment security for any future mining operations.

The first field trial for the UX-1 robot took place in June 2018 in the Kaatiala mine in western Finland. At that point, the robot was still remotely controlled, but it was successful in submerging itself and identifying minerals from a test array of mineral samples.

During the trial at the Idrija mine in December 2018, the robot performed an autonomous dive for the first time and was able to use its multispectral camera to identify minerals in the water.

Staying Connected for Safety

In addition to exploring and mapping flooded mines, robots are also being designed to make mines safer. In the United States, about 1,000 people die in mines each year. Accurate numbers are more difficult to find in a global context, but some sources estimate that up to 12,000

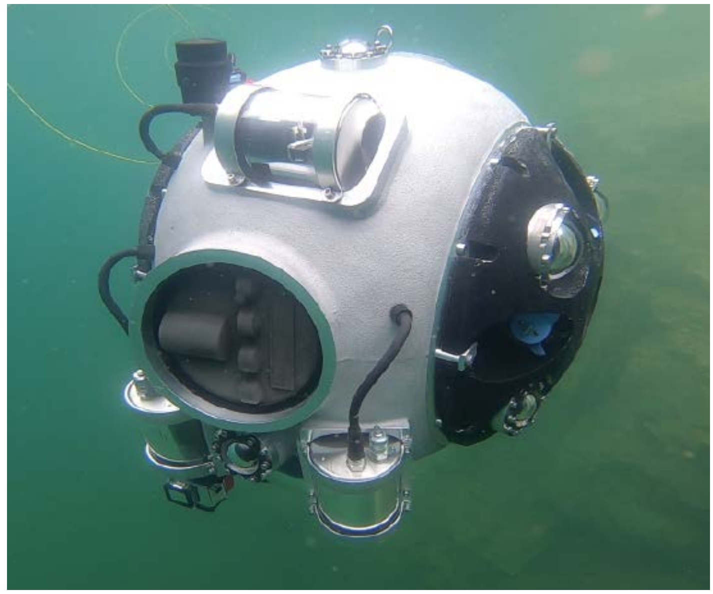
Julius, the robot above, can track people, robots, and machines, as well as monitor environmental conditions, in mines like this one, the research and teaching mine Reiche Zeche in Germany. Credit: Eckardt Mildner

Autonomous and semi-autonomous robots, like this one at the research and teaching mine Reiche Zeche, can be part of the Internet of Things. Credit: Freiberg University of Mining and Technology

miners die each year in mining accidents, mostly in coal mines.

"When there is no one in a mine, no one can be injured or killed," said Helmut Mischo, chair of underground mining methods at Freiberg University of Mining and Technology in Germany. Mischo is part of a multi-institution team that is working to combine robotics and the Internet of Things through an initiative called ARIDuA, or autonomous robots and the Internet of Things in underground mining.

The Internet of Things (IoT) refers to interconnected networks of devices, appliances, or systems that can communicate with each other and exchange data and information. According to the ARIDuA website, "robotics and the IoT have a synergistic relationship: on the one hand, robots can profit from IoT infrastructure, e.g. by using sensor data for better navigation, and on the other hand robots can help to install IoT infrastructure."



The UX-1a robot navigates underwater at the Kaatiala trial site in Finland. The instrumentation seen includes a set of cameras and thrusters that allow the robot to perform basic functions (movement, navigation, mapping). An umbilical cable (yellow) was used for security of operations. Credit: UNEXMiN

An example of an IoT system within a mine would be networked sensors that monitor the mine environment and provide early warnings for dangers, such as gas leaks. When a leak is detected, miners can be evacuated. Robots can be sent in to investigate the leak and explore possible options. The same network that connects the networked sensors can also be used to communicate with and control the robot if it's not autonomous.

One challenge in developing and maintaining an IoT infrastructure within mines is that the mine environment is always changing and expanding, Mischo said. "In a typical factory, the machinery, workstations, and production lines are all stationary, and data, such as electricity and water consumption, can be gathered and processed relatively easily," he said. But everything changes in a mine.

"Mines are expanding continuously, and the work environment changes constantly. Any network being used in mines needs to reinvent itself constantly as the environment changes, which again highlights how a mobile robot, which can expand and maintain the network, and the IoT can work together."

Mischo and his colleagues currently are testing the combination of robotics and IoT at the Reiche Zeche Living Mine, a research and training mine at the Freiberg University of Mining and Technology. Having access to an underground environment is key, Mischo said, because "progress in the surface environment is helpful but not always directly comparable to the underground, irregular, and confined spaces in mines."

At the teaching mine, researchers are testing a mobile robot called Julius and a sensor network that can track people, robots, and machines in the mines as well as monitor environmental conditions. Ultimately, the goal is to make mines safer, using a combination of technology and human labor.

Research Across the Globe

Researchers in other parts of the world are also investigating ways that robots can help make mining safer and more efficient. For example, at the Colorado School of Mines in Golden, Hao Zhang, Andrew Petruska, and colleagues are exploring ways in which humans can effectively use robots in mine environments.

"Current technology is not mature enough to have fully autonomous mines," said Zhang, a computer scientist. "Robots can go into dangerous environments and replace humans there, but final decisions still have to be made by people. People and robots have different skill sets, and we need both to optimize mining operations."

As a result, Zhang and colleagues are focusing on "human-robot teaming, networking, planning, and human-robot interactions" in the context of mines and other underground environments.

Petruska, a mechanical engineer, also highlights the need for teamwork when it comes to robots, humans, and mines. "Computers are very good at some things, such as mathematical stuff and calculations, but not very good at other things that people may find easy," he said.

In the context of mines, robots often find it very difficult to navigate underground and to understand what other robots and people are doing and how to communicate with those robots and people. So Petruska and Zhang are developing robots that can intuitively gauge human intent, analyze human activities, and determine team intent just by observing.

Co-robots, or robots that work alongside humans, are also being developed by researchers at the Council for Scientific and Industrial Research (CSIR) in South Africa. Shaniel Davrajh, a researcher at CSIR, said that a major challenge for the South African mining industry stems from having unique ore bodies at great depths and high inclines.

Researchers launch robot UX-1a for an exploration mission at the Borba shaft in the Idrija mine in Slovenia, 120 meters below the surface. The robot dove to a maximum depth of 26.2 meters in the shaft. Descent into depth lasted 1.5 hours, and rise from the bottom lasted 0.5 hour. Credit: UNEXMiN

"The flexibility and adaptability required to implement robotic solutions currently require high-cost solutions which are outweighed by implementing teams of dedicated, focused, and skilled conventional miners. Therefore, we are now focusing on developing technologies that are specifically human-centered, much like co-robots in the manufacturing industries," said Davrajh.

Among the robotic systems being designed at CSIR is a platform that can assist miners during an early examination process of mines. "Currently, miners have to perform visual and acoustic inspections using a pinch bar to identify and remove loose rock that is at risk of falling to the ground. They do this in unsupported environments, which poses a significant safety risk," Davrajh said.

The robotic platform is equipped with a set of range finders, thermal imaging sensors, and acoustic systems, all of which are operated with neural networks. The robot can go into different environments and identify potential risk areas before the workforce enters. Much of this work is at the proof-of-concept stage.

Conclusions

Although much progress has been made in developing robots that make mining safer and more efficient, much remains to be done, Zajzon said.

"For example, the UX-1 is an amazing robot, but it's not a miracle; we cannot fully reopen a mine with the robot as it is today. However, before reopening a mine, we have to explore and make geological measurements, and that can cost a lot of money. That's where UX-1 can help—the robot can lower the costs of investigating and determining which flooded mines would be economically viable to reopen."

> Robotics and the [Internet of Things] have a synergistic relationship: on the one hand, robots can profit from IoT infrastructure…and on the other hand robots can help to install IoT infrastructure."

Davrajh agrees that robotics in mining is not a panacea for the dangers of working in a mine and the challenges faced by the mining industry.

"There is no 'silver bullet' that will save jobs and the future of many of the operations in South Africa," said Davrajh. "All we are trying to do is provide incremental solutions and gradually increase the arsenal of tools that can help miners work more safely and efficiently."

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AGU Honored with the First Clean Energy DC Award


Members of the AGU team behind the new net-zero energy headquarters building in Washington, D.C., accept the city's first clean energy award. From left: Matt Boyd, Cristine Gibney, Janice Lachance, Mike Andrews, D.C.'s Department of Energy & Environment director Tommy Wells, and Chris McEntee. Credit: Beth Bagley, AGU

As the leader of an innovative, forward looking organization, I am proud to share that AGU received the very first Clean Energy DC Award to honor our commitment to sustainability through our newly renovated headquarters building, the first net-zero energy commercial renovation in Washington, D.C. This award was presented to AGU during the District Sustainability Awards ceremony on 17 April 2019.

Each year, the Washington, D.C., Department of Energy and Environment (DOEE) presents District Sustainability Awards to nonprofits, educational organizations, and private-sector businesses that support sustainable District goals, including energy and water conservation, green building and construction, healthy food access, solar energy production, storm water management, and sustainable waste management. This year, AGU was included in this distinguished class of honorees.

Being the first recipient of the Clean Energy DC Award is not only an honor but also a signal that our building is already an important achievement in sustainability. This is just the beginning of our building's legacy as AGU demonstrates that a building located on a tight urban footprint can operate on a net-zero energy basis, reduce its carbon footprint, and serve as a productive and healthy place to work and meet. Earlier this year, in recognition of this commitment to sustainability, Washington, D.C., mayor Muriel Bowser signed the Clean Energy DC Omnibus Amendment Act of 2018 at AGU's renovated building. This historic piece of legislation will require electricity in the city to come from 100% renewable sources by 2032, among other sustainable initiatives and incentives.

Being the first recipient of the Clean Energy DC Award is not only an honor but also a signal that our building is already an important achievement in sustainability.

The AGU community is incredibly grateful to receive this recognition from the DOEE and its director, Tommy Wells. AGU has appreciated our partnership with the District and its agencies to explore strategies to realize our net-zero energy goals. We now aspire to lead and serve as an example to others of how to implement sustainable solutions and technologies in their own building or renovation projects, and this award demonstrates the impact our building has already had in the local area.

I would like to especially acknowledge the members of our AGU building staff team, including Janice Lachance, Mike Andrews, Matt Boyd, Emily Johnson, Cristine Gibney, Liz Landau, Beth Bagley, Ron Bennett, Sabina Sadirkhanova, Michelle Brown, and Beth Trimmer, for their incredible efforts that made our net-zero energy renovation a reality. The AGU community should be proud of the efforts that went into making our headquarters a model for other buildings to help our society work toward a more sustainable city, country, and world.

By **Chris McEntee** (agu_execdirector@agu.org), Executive Director/CEO, AGU

In Appreciation of AGU's Outstanding Reviewers of 2018

AGU Publications recognizes outstanding reviewers for their work in 2018. Honored reviewers were selected by the editors of each AGU journal.

Peer-reviewed literature plays an important role in advancing science. In addition, there is growing use of peer-reviewed literature in our legal systems and governments as a basis for regulations, policies, and laws. This literature also provides reliable scientific information for advisory groups such as the Intergovernmental Panel on Climate Change and the National Academies.

Quality peer review is thus a critical part of the social contract between science and society. As the uses for this literature have grown, so has the complexity of papers, which now typically include more authors bringing more techniques, data, simulations, and results.

This increase in complexity, in turn, has increased the challenge and role of reviewing. The outstanding reviewers listed here have all provided in-depth evaluations that greatly improved the final published papers, often over multiple rounds of revision.

Many Reviewers: A Key Part of AGU Journals

While we honor these few outstanding reviewers, we also acknowledge the broad efforts by the many AGU reviewers in helping ensure the quality, timeliness, and reputation of AGU journals. In 2018, AGU received over 15,600 submissions (up from 14,300 submissions received in 2017) and published nearly 6,600 articles (up from 6,400 in 2017). Many of these submissions were reviewed multiple times—in all, 17,242 reviewers completed 37,674 reviews in 2018 compared with 34,000 reviews completed in 2017.

This has happened in the past year while every AGU journal worked to shorten the time

Our thanks are a small recognition of the large responsibility that reviewers shoulder in improving our science and its role in society.

from submission to first decision and publication or maintained already industry-leading standards. Several AGU journals regularly return first decisions within 1 month of submission, and most others now do so within 2 months. Reviewers represent a key part of this improvement.

Our thanks are a small recognition of the large responsibility that reviewers shoulder in improving our science and its role in society. Editorials (some already published, some upcoming), along with recognition lists, express our appreciation.

Additional Thanks

In addition, we are working to highlight the valuable role of reviewers through events at the Fall Meeting and other meetings.

We are extending subscription benefits to those reviewers who repeatedly provide quality reviews. Each reviewer also receives a discount on AGU and Wiley books. We will continue to work with the Open Researcher and Contributor Identification (ORCID) network to provide official recognition of reviewers' efforts so that reviewers receive formal credit there. To date, we have over 49,000 ORCIDs linked to GEMS user accounts, compared with 39,000 at this time last year.

Getting Your Feedback

We are working to improve the peer review process itself, using new online tools. We have designed a short questionnaire for reviewers to provide feedback and will send a link after each review is completed.

We value your feedback, including ideas about how we can recognize your efforts even more, help improve your experience, and increase your input on the science.

We look forward to hearing from you. If you'd like to respond directly, feel free to take our survey.

Once again, thanks!

By **Matt Giampoala** (mgiampoala@agu.org), Vice President, Publications, AGU; and **Lisa Tauxe,** Chair, Publications Committee, AGU

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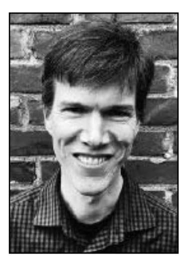

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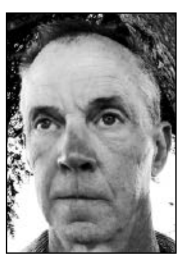

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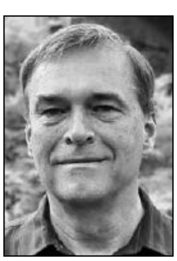

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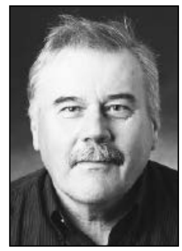

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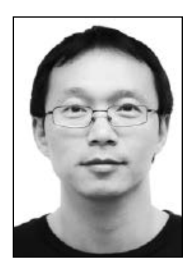

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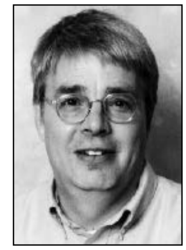

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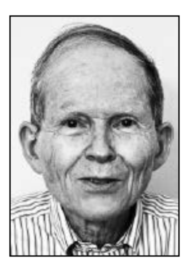

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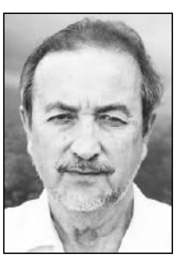

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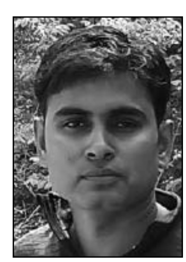

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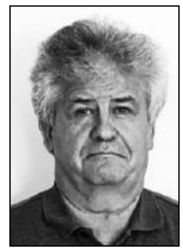

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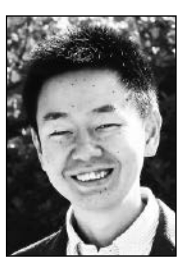

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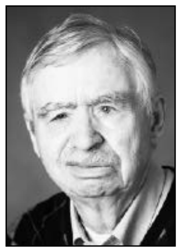

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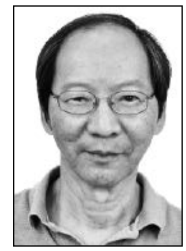

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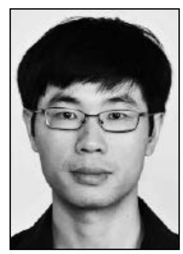

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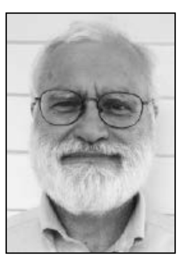

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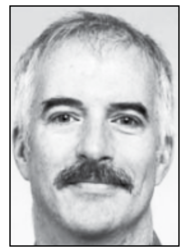

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Models Show Radiation Damage to Astronauts in Real Time

EOS CENTENNIAL COLLECTION

An artist's rendering of the Orion spacecraft that NASA is planning to use on future deep-space missions. Credit: NASA Orion Spacecraft, CC BY-NC-ND 2.0 (bit.ly/ccbynd2-0)

In a list of the thousands of lucky factors that have enabled life to flourish on Earth, the planet's magnetism should rank somewhere near the top. Earth's magnetic field acts as a kind of shield, protecting the surface from a constant stream of solar energetic particles (SEPs) that cause mutations to DNA that would make life as we know it impossible. This radiation poses a real danger to astronauts who leave the protection of Earth's magnetic field.

Ordinarily, the risk of solar radiation to deep-space travelers is relatively low and constant, a steady background of small doses. But occasionally, following space weather events like coronal mass ejections, the Sun can release a much denser barrage of SEPs that greatly amplifies the danger to human health—the same way a quick, torrential downpour will soak you more thoroughly than a long, misty morning. As NASA plans longer missions deeper into space, researchers are trying to understand what type of risk these acute bursts of SEPs will pose to astronauts.

Here *Mertens et al.* demonstrate a new system of models that could help show, in real time, both how many SEPs astronauts are exposed to and how much damage the exposure could cause to our biology. The researchers designed the project specifically for NASA's Orion Multi-Purpose Crew Vehicle, which the agency plans to use in future missions to the Moon and Mars. To calculate how much radiation an astronaut is exposed to, the first model draws data from six dosimeters—sensors that detect incoming radiation—placed around the inside of the craft in the same locations the crew would be found. A second model then translates the exposure into biological risk, especially in blood-forming organs (bone marrow, thymus, spleen), which are the most sensitive to radiation. This second model also shows how the radiation exposure may negatively affect an astronaut's performance during the mission.

This system of models is slated for use on upcoming missions. Researchers have not yet been able to test it, however, in a deep-space SEP event. Instead, they ran a simulation using data drawn from various satellites during a historically dangerous SEP event in October 1989. In this simulated experiment, the researchers report, the models performed well, averaging 33% uncertainty across the duration of the event.

Although these results are encouraging, the researchers note that these experiments assume that the incoming radiation is isotropic, meaning that it comes from all directions in a relatively equal distribution, whereas actual incoming radiation is anisotropic. The authors are planning future work to assess how anisotropy influences uncertainty in the organ dose model, a vital question if humanity plans to explore space beyond the protection of Earth's magnetic field. (*Space Weather,* https://doi.org/10.1029/2018SW001971, 2018) **—David Shultz, Freelance Writer**

New Analysis Provides a Fresh View of the Atmosphere on Venus

EOS CENTENNIAL COLLECTION

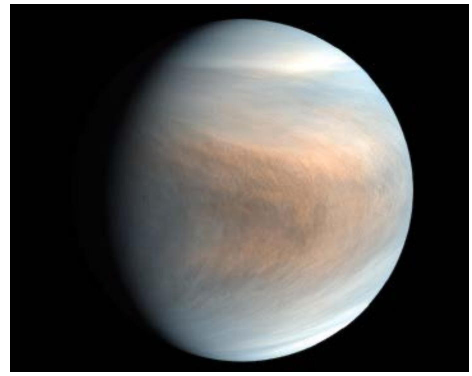
Venus is Earth's closest planetary neighbor and the nearest in size to our "Blue Marble," yet many questions remain about its atmosphere, in part because of challenges in generating fine-scale analyses. Research on the atmosphere of Venus typically results in a vertical resolution of between 0.4 and 0.7 kilometer, which is too coarse to observe small-scale atmospheric features. Phenomena like the Venusian "cold collar," a distinct temperature minimum about 60 kilometers above the surface at high latitudes, remain poorly understood because remote sensing algorithms cannot clearly delineate them.

Remotely sensed data captured by the European Space Agency's Venus Express Radio Science Experiment (VeRa) and the Japan Aerospace Exploration Agency's Akatsuki Radio Science mission underlie many analyses of the Venusian atmosphere. These data are collected through radio occultation, which detects bends in radio waves caused by Venus's atmosphere when the planet passes between the spacecraft and Earth. The data are commonly evaluated using the geometrical optics (GO) method; however, GO often blurs radio rays and cannot decipher rays spreading along multiple pathways. The inability to capture ray propagation plays a significant role in limiting the vertical resolution in research outputs.

In a new study, *Imamura et al.* address the resolution problem by applying an analytical twist to the standard data. The researchers evaluated the radio occultation data using a radio holographic method known as full spectrum inversion (FSI); this is the first time the technique has been applied to Venusian atmospheric data. Among the differences in the two approaches, FSI calculates the arrival time of the radio signal to Earth as a function of the wave frequency; in comparison, GO obtains the radio wave frequency as a function of time.

By using FSI, the researchers obtained an unprecedented vertical resolution (less than 100 meters) in the remotely sensed data. The finer resolution revealed small temperature structures in the atmosphere that the authors suggest are manifestations of atmospheric gravity waves and thin turbulent layers. Atmospheric gravity waves and turbulent layers generated by those waves play crucial roles in Earth's middle atmosphere but have not previously been well studied on Venus, partly because of the coarse-scale analysis.

The findings also clearly delineate the cold collar temperature minimum hovering around the tops of clouds in the atmosphere. The authors suggest that the sharp gradient was created by adiabatic cooling. Such inference was not possible using the GO method.



New research offers a new look at Venus's atmosphere by measuring the bend and scatter of radio waves as they pass through the planet's atmosphere. This false-color image taken by Japan's Venus probe Akatsuki shows atmospheric fine structures. Credit: JAXA

The study's conclusions yield a more precise view of Venus's atmospheric temperature profile than has previously been published, and both results offer new insights into the atmospheric dynamics on Venus. The radio holographic analysis also provides many possibilities for observing narrow vertical structures in the atmospheres of other far-flung planets. (*Journal of Geophysical Research: Planets,* https://doi.org/10.1029/2018JE005627, 2018) **—Aaron Sidder, Freelance Writer**

Can Patches of Cold Air Cause Thunderstorms to Cluster?

In portions of Earth's atmosphere, initially scattered thunderstorm clouds display a spontaneous tendency to cluster. Although this convective self-aggregation is believed to play an important role in the organization of squall lines, hurricanes, and the most important tropical weather cycle, the Madden-Julian Oscillation, the dynamics behind the phenomenon are still poorly understood.

Previous researchers have proposed that self-aggregation is due to differences in heat loss from cloudy regions compared with clear ones, but to date no direct correlation has been found. Now *Haerter* explores whether convective self-aggregation could instead result from interactions between cold pools, 10- to 100-kilometer-wide pockets of cold air that develop when evaporative cooling occurs beneath precipitating cumulonimbus and other convective clouds.

To further investigate the role of these small-scale interactions, the author developed a series of simple conceptual models that treat cold pool–driven self-aggregation as a critical phenomenon. The findings indicated that collisions between multiple cold pools can lead to convective self-aggregation but that the triggering of a single cold pool does not.

By bridging the fields of statistical physics and atmospheric science, the author's research offers novel insights into the potential linkage between small-scale interactions and universal behavior. The results offer a compelling mechanism for explaining how interactions between cold pools, rather than differences in radiation, ultimately organize large-scale atmospheric phenomena. (*Geophysical Research Letters,* https://doi.org/10.1029/2018GL081817, 2019) **—Terri Cook, Freelance Writer**

The Accidental Particle Accelerator Orbiting Mars

EOS CENTENNIAL COLLECTION

This artist's rendering of the Mars Express spacecraft shows the 40-meter-long antenna used by the Mars Advanced Radar for Subsurface and Ionosphere Sounding (MARSIS), the craft's powerful ground-penetrating radar, which can also accelerate charged particles in the planet's ionosphere. Credit: Alex Lutkus/ESA

Scientists have known for decades that when you put a powerful radio transmitter into space, the radio waves can energize the plasma that surrounds Earth, creating beams of high-energy ions and electrons. This phenomenon—dubbed sounder-accelerated particles (SAP)—was theoretically proposed in the 1970s and first detected in Earth orbit by the Soviet satellite Interkosmos 19 in 1979.

But it wasn't until the mid-2000s that scientists identified this phenomenon occurring on another planet, thanks to the Mars Express mission. The European Space Agency craft, which reached Mars in 2003, was equipped with a powerful ground-penetrating radar designed mainly to search for underground reservoirs of liquid water. But it could also be used to probe the layers of Mars's ionosphere. Shortly after operations began in Mars orbit, preliminary analysis showed that these pulses of radio waves were also energizing the ions themselves, similar to what had been observed near Earth.

Now *Voshchepynets et al.* have taken a deep dive into over 10 years of data from Mars Express to learn more about the underlying physics behind SAP and how they may differ in the Martian environment.

By combining data from the radar and the craft's ion mass analyzer (IMA), the authors could see when the IMA was detecting oxygen ions that were being accelerated by the radar's pulses, reaching energies as high as 800 electron volts. The data also showed that these beams were usually generated when the radar was transmitting at frequencies close to the plasma's own resonant frequency, the natural frequency at which it pitches and heaves.

This result is similar to what has been observed from Earth-orbiting spacecraft, where spacecraft sounders can form instabilities in the plasma that build up and accelerate particles. However, the authors' analysis of the conditions in Mars orbit shows that this mechanism could accelerate the ions to only a fraction of an electron volt, not the hundreds observed by Mars Express.

To explain the high-energy ions, the team suggests that when the spacecraft's radar is active, the voltage applied to the antenna causes a negative charge to build up on the spacecraft itself. When the radar's pulse is over, positive ions in the ambient plasma are then accelerated toward the spacecraft.

The ability of Mars Express to generate such particle beams could lead to a new way to study planetary ionospheres, the authors say, one where spacecraft actively probe their environments and manipulate the plasma around them to detect hard-to-find ions. (*Journal of Geophysical Research: Space Physics,* https://doi.org/10.1029/2018JA025889, 2018) **—Mark Zastrow, Freelance Writer**

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Geodesy

The UNAVCO Board of Directors seeks Applicants to the position of President.

Located in picturesque Boulder, Colorado, UNAVCO is a non-profit corporation that supports and promotes Earth science by advancing high-precision geodetic positioning, timing, and remote sensing for basic research, environmental studies, environmental monitoring and hazards mitigation. Our membership is composed of international education, research, and operational institutions with a commitment to scholarly research, outreach and scientific application. The recent announcement of retirement by our esteemed President Dr. M. Meghan Miller requires that the UNAVCO Board of Directors fill the position of President. The President will report directly to the UNAVCO Board of Directors, which is elected by its membership.

Challenges for UNAVCO's next President: Geodetic science and its applications have become deeply embedded within the mesh of science and society. This expansion of geodetic science and technology has also spurred the need for increasing investments in instrumentation to improve the resolution, distribution, and reliability of data being delivered to the UNAVCO Community and its many pursuits and applications. UNAVCO is also committed to improving the technical skills and scientific well-being of its Community while navigating within increased political and economic pressures. UNAVCO will have to adapt to this dynamic environment and will need guidance from a President with thoughtful vision and the ability to execute on that vision.

The Board of Directors seeks a dynamic leader with:

o A demonstrated record of excellence, vision and leadership in Earth science;

o A broad understanding of the scientific and operational applications of geodetic technology in service of basic research, environmental monitoring and hazards mitigation;

o Highly-developed leadership, communication, and interpersonal skills to represent UNAVCO in scientific, government, and commercial venues;

o A demonstrated ability to promote a diverse and inclusive environment;

o A demonstrated ability to lead, communicate with, and inspire the diverse employees of the facility and to work effectively as a team member;

o A demonstrated ability to promote consensus among researchers and managers with diverse points of view;

o Knowledge of UNAVCO's sponsor agencies (NSF, NASA, USGS), their sister agencies and associated governmental structures and procedures;

o Strong management skills and business knowledge with a demonstrated ability to lead within a cost and schedule constrained environment;

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AIR FORCE SCIENCE & TECHNOLOGY FELLOWSHIP PROGRAMS
Postdoctoral and Senior Research Awards

The Air Force Science & Technology Fellowship Program (AF STFP) offers nationally competitive fellowship awards to postdoctoral and senior scientists to perform collaborative research at U.S. Air Force research facilities across the country. Since 1966, the Air Force S&T Enterprise has hosted over 1,000 fellows under the NRC Research Associateship Programs and many of these researchers have gone on to successful careers in government laboratories. The AF STFP continues this tradition of providing high quality research opportunities with Air Force scientists and engineers at Air Force Research Laboratory, the Air Force Institute of Technology, and the U.S. Air Force Academy.

We are actively seeking highly qualified candidates including recent doctoral recipients and senior researchers. Applicants should hold, or anticipate receiving, an earned doctorate in science or engineering. Applications are accepted during four annual review cycles with **deadlines of February 1, May 1, August 1, and November 1.**

Awardees have the opportunity to:
- Conduct independent research in an area compatible with the interests of the Air Force laboratories
- Devote full-time effort to research and publication
- Access the excellent and often unique facilities of the Air Force
- Collaborate with leading scientists and engineers

Benefits of an AF STFP award include:
- Base stipend starting at $76,542, which is increased based on years of experience past the doctoral degree
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For detailed program information, visit **www.nas.edu/afrl** or send an e-mail to **rap@nas.edu.**

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Application Details: The minimum term of the employment is negotiable but the expectation is 2-4 years. Applications must include: 1. A complete vita 2. The names and addresses of three or more references 3. A statement outlining the applicant's vision for UNAVCO, and 4. A statement that addresses past and/or potential contributions to diversity, equity and inclusion. Follow this link, https://unavcocareers.silkroad.com click on President and select "Apply".

Review of applications will begin immediately and continue until the position is filled. All inquiries and nominations are invited via email to: hr@unavco.org

Please note: We are unable to provide sponsorship for work authorization. UNAVCO is an Equal Employment Opportunity/Affirmative Action employer.

Interdisciplinary

Assistant Professor (tenure track) in Paleoclimate Sedimentology

The Faculty of Geosciences and the Environment (FGSE) of the University of Lausanne invites applications for a professorship in Paleoclimate Sedimentology, to be based in the Institute of Earth Sciences (ISTE).

We are looking for an excellent sedimentologist who focuses on the reconstruction of past climate changes (including sedimentary, paleoclimate, biological and paleoceanography changes) at geological timescales using the stratigraphic and sedimentary record. We seek a candidate who can provide an innovative interpretation of sedimentary archives, using laboratory, and field techniques and reconstructing Earth system history. The ideal candidate should have a strong background in geology, a strong commitment to field-based research and a willingness to contribute to field-based teaching.

The successful candidate will actively participate in the research activities of the Institute of Earth Sciences, will teach in the Bachelor of Geosciences and Environment and in relevant Masters taught by the FGSE, and will supervise masters and doctoral students.

Appointment will be at the Assistant Professor level (tenure track). However, exceptionally, we will consider outstanding candidates for direct appointment to the Associate or Ordinary Professor level, notably if this corresponds with our equal opportunity objectives.

Application deadline: August 24th, 2019

(23:59 Swiss time GMT+2)

Details how to apply on: https://bit.ly/2PPF6Da

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Our lab works at the interface of molecular evolution, synthetic biology, biochemistry, origins of life and astrobiology. We aspire to resurrect ancient proteins and synthetically engineered metabolisms as proxies for ancient biogeochemistry.

We are interested in outstanding applicants with the following qualifications:

- Formal Training in Earth or Biological Sciences with emphasis on geobiology or microbiology
- Research experience in microbial culturing of microbes, preferably in molecular biology and genomics
- Research experience in stable isotope probing is highly preferred

To apply: Submit to Ross Monasky the following via email (rmonasky@email.arizona.edu):

- Cover letter describing your experience, training, expertise and motivation
- CV with a publication list
- Names and contact information for 3 references
- Include "CYANOPD" in the Subject line

The project is funded by the National Science Foundation, available immediately and covers full salary and benefits.

Outstanding UA benefits include health, dental, and vision insurance plans; life insurance and disability programs; paid vacation, sick leave, and holidays; UA/ASU/NAU tuition reduction for the employee and qualified family members; state retirement plan; access to UA recreation and cultural activities; and more. The University of Arizona has been listed by Forbes as one of America's Best Employers in the United States. World at Work and the Arizona Department of Health Services have recognized us for our innovative work-life programs.

Ocean Sciences

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Jefferson Science Fellows spend one year at the U.S. Department of State or the U.S. Agency for International Development (USAID) for an on-site assignment in Washington, D.C. that may also involve travel to U.S. foreign embassies and/or missions.

The fellowship is open to tenured, or similarly ranked, academic scientists, engineers, and physicians from U.S. institutions of higher learning. Applicants must hold U.S. citizenship and will be required to obtain a security clearance.

The deadline for applications is **October 31, 2019 at 5 PM EST**. To learn more about the Jefferson Science Fellows program and to apply, visit **www.nas.edu/jsf.**

The Jefferson Science Fellows program is administered by the National Academies of Sciences, Engineering, and Medicine and supported by the U.S. Department of State and the United States Agency for International Development.

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NRC RESEARCH ASSOCIATESHIP PROGRAMS

The National Academy of Sciences, Engineering, and Medicine offers postdoctoral and senior research awards on behalf of 23 U.S. federal research agencies and affiliated institutions with facilities at over 100 locations throughout the U.S. and abroad.

We are actively seeking highly qualified candidates including recent doctoral recipients and senior researchers. Applications are accepted during four annual review cycles (**with deadlines of, August 1, November 1, February 1, May 1).**

Awardees have the opportunity to:

- conduct independent research in an area compatible with the interests of the sponsoring laboratory
- devote full-time effort to research and publication
- access the excellent and often unique facilities of the federal research enterprise
- collaborate with leading scientists and engineers at the sponsoring laboratories

Benefits of an NRC Research Associateship award include:

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DESIRED SKILLS AND EXPERIENCE

Applicants should hold, or anticipate receiving, an earned doctorate in science or engineering. Degrees from universities abroad should be equivalent in training and research experience to a degree from a U.S. institution. Some awards are open to foreign nationals as well as to U.S. citizens and permanent residents.

ABOUT THE EMPLOYER

The National Academies of Sciences, Engineering, and Medicine's Fellowships Office has conducted the NRC Research Associateship Programs in cooperation with sponsoring federal laboratories and other research organizations approved for participation since 1954. Through national competitions, the Fellowships Office recommends and makes NRC Research Associateship awards to outstanding postdoctoral and senior scientists and engineers for tenure as guest researchers at participating laboratories. A limited number of opportunities are available for support of graduate students in select fields.

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Leibniz-Institut für Ostseeforschung Warnemünde IOW

Universität Rostock Traditio et Innovatio

At the Leibniz Institute for Baltic Sea Research – Warnemuende (IOW) the position of the

Director

is available from 1st October 2021.

The IOW is a member of the Leibniz Association (WGL e.V.). With its four scientific departments Physical Oceanography and Instrumentation, Marine Chemistry, Biological Oceanography and Marine Geology, it conducts basic marine research within the framework of a multi-year research programme. The focus is on coastal, marginal and shelf seas with a special focus on the Baltic Sea. Through an administrative agreement with the Federal Maritime and Hydrographic Agency, the IOW is charged with the tasks of environmental monitoring of the Baltic Sea within the framework of HELCOM.

The position of the director encompasses also a

W3 professorship for Earth Systems Analysis

at the University of Rostock.

IOW and the University of Rostock invites applications of outstanding scientists in earth system analysis – preferably in marine science. Experiences in leadership, science administration and management are required. The Director is responsible for the scientific management of the IOW and for representing the Institute externally and internally. In particular, impulses for research design and structures and the lead in the program budget of the IOW as well as constructive cooperation in the profile line Maritime Systems of the Interdisciplinary Faculty of the University of Rostock are expected. The teaching obligation is 2 SWS.

For further inquiries, please contact:
Prof. Dr. Detlef Schulz-Bull, chair of appointments committee
Telefon: +49 381 5197 310
e-mail: detlef.schulz-bull@io-warnemuende.de

Qualifications are as per § 58 of the Higher Education Act of the State of Mecklenburg-Vorpommern (LHG M-V). Details will be explained on request.

Please direct your application with the usual documents ***no later than 30th June 2019*** preferably by e-mail to:

dekan.mnf@uni-rostock.de or to

Universität Rostock
Dekan der Mathematisch-Naturwissenschaftlichen Fakultät
18051 Rostock

For the full announcement, please consult the internet at:
www.uni-rostock.de/stellen/professuren/

respectively by the International Hydrographic Organization, the International Federation of Surveyors, and the International Association of Cartographers. SOSE includes two academic divisions, Marine Science, and Coastal Sciences, and several R&D centers including: Hydrographic Science Research Center, Center for Fisheries Research and Development, and Thad Cochran Marine Aquaculture Center. The Division of Marine Science is based at the NASA Stennis Space Center where Marine Science faculty benefit from close working relationships with a number of on-site federal agencies, including the Naval Research Laboratory-Stennis Space Center, the Naval Oceanographic Office, the Naval Meteorology and Oceanography Command, the USGS and NOAA, including the National Data Buoy Center.

Applicants must hold a M.S. degree in hydrography, oceanography, or a related field with 5 years or more of hydrographic surveying experience. Preference will be given to candidates with a Ph.D. in hydrography, oceanography, or a related field and post-doctoral experience, and a demonstrated record of service, grant development, communication, and commitment to diversity. The candidate is expected to coordinate, execute, and continue to develop a comprehensive academic program in hydrography, at the undergraduate and graduate level, in accordance with International Hydrographic Organization (IHO) standards. The undergraduate program is a 4-year curriculum providing a Bachelor of Science degree in Marine Science with emphasis in Hydrography. The graduate program is an intensive 1-2 year curriculum with significant classroom coursework and field exercise, including a capstone project. The successful candidate is expected to develop and deliver courses in hydrography and related sciences and should demonstrate the potential to contribute across disciplines and promote the continued interdisciplinary growth of the academic and research programs within the SOSE. The candidate can expect to be involved in research activities with the Hydrographic Science Research Center, but the primary focus of this position is teaching. Salary packages will be nationally competitive and commensurate with experience. Applications must be submitted online at https://jobs.usm.edu. For inquiries about the position, contact Stephan Howden, Chair of the Search Committee, at 1-228-688-5284 or Stephan.howden@usm.edu. Review of applications begins 1 May 2019 and continues until the position is filled, with an anticipated start date of August 2019.

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In the photo, from left to right, Ryan Gold, Maddie Hille, and Chris DuRoss enjoy the shade while they discuss the latest observations.

—Jaime Delano, U.S. Geological Survey, Golden, Colo.

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